

**ADDRESSING CLIMATE CHANGE ADAPTATION THROUGH
TRANSIT ASSET MANAGEMENT: A CASE STUDY OF MARTA**

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by

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ADDRESSING CLIMATE CHANGE ADAPTATION THROUGH TRANSIT ASSET MANAGEMENT: A CASE STUDY OF MARTA

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To Mom and Dad

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LIST OF SYMBOLS AND ABBREVIATIONS

AAAPUL	Average Age of Assets as a Percentage of their Useful Life
AASHTO	American Association of State Highway Transportation Officials
ALDOT	Alabama Department of Transportation
AMP	Asset Management Plan
AMPLE	Asset Management Program Learning Environment
AMS	Asset Management System
APRM	Asset Performance Review Maintenance
APT	Adaptation Priority Task Force
APTA	American Public Transportation Association
BART	Bay Area Rapid Transit
BMS	Bridge Management System
BRT	Bus Rapid Transit
CARE	Climate Adaptation Resiliency Evaluation
CEQ	Council on Environmental Quality
CEQA	California Environmental Quality Act
CIP	Capital Improvement Program
CMMS	Computerized Maintenance Management Systems
CNG	Compressed Natural Gas
CTA	Chicago Transit Authority
DOAV	Department of Aviation
DOT	Department of Transportation
DRP	Disaster Recovery Plan
DRPT	Department of Rail and Public Transit

EAM	Enterprise Asset Managment
EIS	Environmental Impact Statement
EMS	Environmental Management System
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GCM	Global Climate Models
GDP	Geo Data Portal
GIS	Geographic Information System
GRTC	Greater Richmond Transit Commission
GWRI	Georgia Tech Water Resources Institute
HVAC	Heating, Ventilation, and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
ISTEA	Intermodal Surface Transportation Efficiency Act
KPI	Key Performance Indicator
LCARE	Life-Cycle Asset Rehabilitation and Enhancement
LEED	Leadership in Energy and Environmental Design
LR	Lloyd's Register
LU	London Underground
MAP-21	Moving Ahead for Progress in the 21 st Century
MARC	Maryland Area Regional Commuter
MARTA	Metropolitan Atlanta Rapid Transit Authority
MATLAB	Matrix Laboratory
MBTA	Massachusetts Bay Transportation Authority

MMIS	Maximus Management Information System
MMS	Maintenance Management System
MNR	Metro-North Railroad
MOWIS	Maintenance of Way Information System
MPO	Metropolitan Planning Organization
MTA	Metropolitan Transit Authority
MUNI	Municipal Railway
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NJ TRANSIT	New Jersey Transit Corporation
NOAA	National Oceanic and Atmospheric Administration
NR	Normal Replacement
NYCT	New York City Transit
ODOT	Oregon Department of Transportation
OPM	Ordered Probit Model
OSHA	Occupational Safety and Health Administration
PANYNJ	Port Authority of New York and New Jersey
PASS	Privatized Assets Support System
PM	Preventive Maintenance
PMS	Pavement Management System
PPP	Public-Private Partnership
PROGGRES	Program Guidance and Grant Evaluation System
PTMS	Public Transportation Facilities and Equipment and Equipment Management System
RTAMS	Regional Transit Asset Management System
RTCI	Regional Transit Capital Inventory

RTP	Regional Transportation Plan
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
SEPTA	Southeastern Pennsylvania Transportation Authority
SGR	State of Good Repair
SLR	Sea Level Rise
SMD	Structures Maintenance Database
SMS	Subway Maintenance System
SOP	Standard Operating Procedure
SPC	Statistical Process Control
SRES	Special Report on Emissions Scenarios
TAM	Transit Asset Management
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21 st Century
TERM	Transit Economic Requirements Model
TfL	Transport for London
TIFIA	Transportation Infrastructure Finance and Innovation Act
TIP	Transportation Improvement Plan
TMA	Transportation Management Areas
TOD	Transit-Oriented Development
TRAC	Transit Research Analysis Committee
TRB	Transportation Research Board
TTC	Toronto Transit Commission
USGCRP	U.S. Global Change Research Program
USGS	United States Geological Survey
UTC	University Transportation Center

VDOT

Virginia Department of Transportation

VPA

Virginia Port Authority

WMATA

Washington Metropolitan Area Transit Authority

SUMMARY

This thesis conducts a case study of how MARTA could address climate change adaptation through its transit asset management program. Two climate-modeling approaches are utilized to project potential future climate scenarios within MARTA's service area to identify significant climate stressors. These climate stressors are used to help identify vulnerable assets, operations, and locations in the MARTA system through several interviews conducted with key MARTA staff. The results of this basic climate vulnerability assessment are used to develop a series of short-term and long-term adaptation strategies that address these vulnerabilities. Next, a framework is proposed for addressing climate adaptation through MARTA's existing asset management program. Finally, the thesis proposes a general framework that other transit agencies could utilize to address climate adaptation through their asset management programs.

The results of the climate vulnerability assessment indicate that the MARTA service area is likely to experience longer exposure to higher temperatures, flooding, wider variations in temperature, droughts, and more frequent high-wind events. Of these stressors, the MARTA system is most vulnerable to the effects of extreme and prolonged heat as well as flooding caused by intense precipitation events. Adaptation strategies to address these vulnerabilities include more frequent inspection of HVAC systems on buses and rail vehicles, increasing pumping capacity at underground rail stations, and incorporating low-impact developments into surrounded station areas.

The limitations of the results of this case study and areas for further research from these limitations are also presented.

CHAPTER 1

INTRODUCTION

The Federal Transit Administration (FTA) began its State of Good Repair (SGR) Initiative to address the worsening condition of the nation's public transportation assets -- primarily caused by aging along with steady or declining federal funding support relative to rehabilitation and replacement needs. The purpose of the initiative is to improve the state of repair of the nation's transit assets through federal resources in the form of technical assistance and grant programs (such as bus fleet replacement). The initiative has also explored strategies that agencies can adopt to maximize the effectiveness of their limited funds towards achieving a state of good repair. One of these strategies is to develop and implement an asset management system (also referred to as a transit asset management system). A transit asset management (TAM) system allows a transit agency to better understand the condition of its assets, schedule maintenance activities, and prioritize long-term capital expenditures.

A factor that is making an increasing contribution to the deterioration of the nation's transit assets is climate change. The effects of climate change -- such as rising sea levels, more intense precipitation, and more frequent heat waves -- are expected to intensify over the next several decades even if aggressive efforts are taken to reduce the amount of greenhouse gases currently expelled into the atmosphere [1]. Therefore, the transit industry and the FTA have begun to investigate how the effects of climate change are expected to specifically affect transit assets and operations and what adaptation strategies transit agencies can use to address these effects.

The objective of this thesis is to identify and recommend ways that a transit agency can incorporate climate adaptation strategies into an existing transit asset management system. This involves assessing what changes to the local climate are projected to occur as effects of climate change; assessing how the effects of climate

change might impact the agency's assets and operations; characterizing the structure and maturity of the transit asset management system currently in place; identifying and prioritizing potential climate adaptation strategies; and finally identifying existing processes and/or standard operating procedures that could be utilized to implement a climate adaptation plan.

1.1 Problem and Motivation

The transit agency studied in this thesis is the Metropolitan Atlanta Rapid Transit Authority (MARTA), which serves the City of Atlanta, Fulton County, and Dekalb County. MARTA's service area covers 498 square miles and over 1.5 million people living in the Atlanta metropolitan region, which itself covers 2,645 square miles and has over 4.5 million residents [2]. The agency operates 132 bus routes covering approximately 1,000 route miles, with 621 buses. The agency also operates 175 paratransit vehicles and 450 non-revenue vehicles. The MARTA rail system began operation in 1979 with four lines serving 38 stations. It includes approximately 48 miles of track, and operates with 318 rail vehicles. Annual ridership of the entire system is over 105 million trips (approximately half a million per day) [3]. Figure 1 is a map of MARTA's rail system.

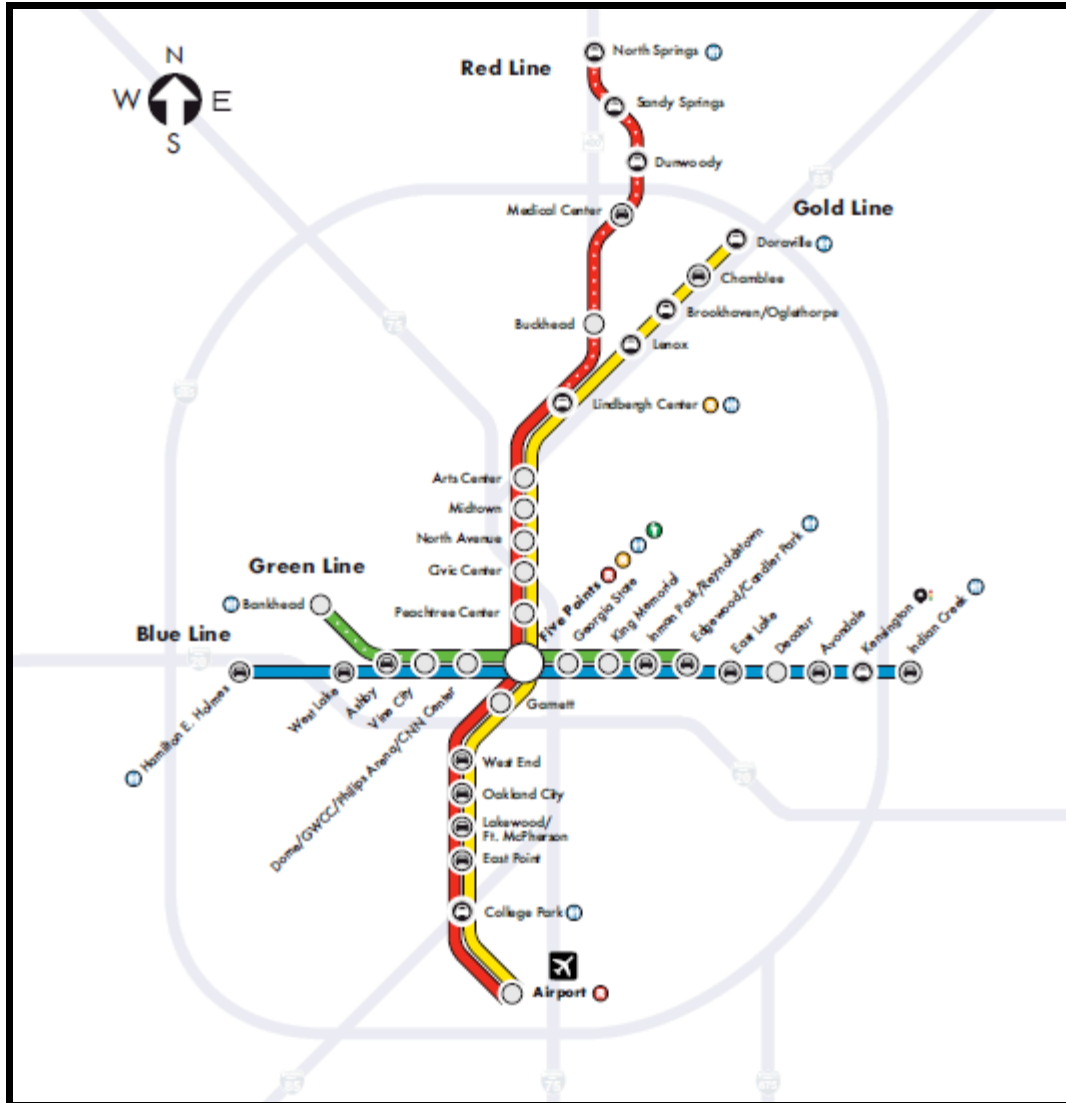


Figure 1. MARTA Rail System Map

MARTA's system is considered a maturing one in the sense that many of its assets, particularly on the rail system, are getting to the point when they will require overhaul or replacement [3]. As a result, MARTA has put significant effort over the past several years into developing a robust transit asset management system to better inform key staff and decision-makers on the overall condition of its assets and utilize this information to better prioritize capital projects [4]. In the process of developing this asset management program, the agency has an opportunity to address climate changes and hazards systematically and system-wide as different elements and portions of the system

get overhauled or replaced. MARTA's definition of state of good repair (SGR) emphasizes maintaining assets in a functioning condition over eliminating the backlog of investment needs or replacing assets based solely upon their age. By this definition approximately 80 to 90 percent of MARTA's assets were estimated to be in a state of good repair in 2010. However, MARTA expects maintaining SGR to be a continuing challenge in the future [3]. This implies that climate change considerations will likely occur within the context of SGR decision making, making the agency's asset management program an appropriate platform that can be used to adapt MARTA's services and system to anticipated climate changes. It appears therefore that asset management platforms will be highly useful decision making systems in which to address climate change issues: balancing SGR needs with the risks of climate hazards and the need for system resiliency.

1.2 Thesis Outline

The remainder of this thesis is composed of the following chapters. Chapter 2 reviews relevant literature on state of good repair efforts, transit asset management, and climate change adaptation in the transit industry. Chapter 3 discusses the methodology used as part of the case study of the MARTA system. Chapter 4 utilizes two climate-modeling approaches to identify the most significant climate stressors that will impact MARTA's service area. Chapter 5 assesses how the climate stressors identified in Chapter 4 might impact MARTA's assets and operations based on historical experience with extreme weather events and the professional experiences of MARTA's staff. Chapter 6 identifies potential climate adaptation strategies that could be adopted at MARTA to address the agency's vulnerabilities to the effects of climate change. Chapter 7 describes and characterizes MARTA's current transit asset management program and a proposes a framework for incorporating the adaptation strategies identified in Chapter 6 into MARTA's existing transit asset management system. Chapter 8 discusses a general

framework that other transit agencies can use to address climate change adaptation through transit asset management. Finally, Chapter 9 provides some brief conclusions on the work conducted as well as potential areas for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of important literature related to the thesis topic. The literature reviewed in this section covers the topics of state of good repair, transit asset management, and climate adaptation. Essentially, the key documents on these three topics are reviewed in detail to provide a broad knowledge base for addressing the impacts of climate change on public transportation assets and services, using asset management principles. The chapter also demonstrates the importance of climate change adaptation processes to the public transportation industry.

2.1 State of Good Repair

2.1.1 Introduction

The term “state of good repair” currently has no uniform definition for all transit agencies. While this issue of definition is expected to be resolved as a result of the passage of the Moving Ahead for Progress in the 21st Century (MAP-21) legislation in the summer of 2012, the FTA has already begun its State of Good Repair (SGR) Initiative. The term and the subsequent initiative had their roots in both a directive from the 2008 Transportation-HUD Appropriations bill and a letter from several Senators requesting that the FTA conduct an assessment of the condition of the nation’s largest transit agencies [5]. The FTA’s response to these two similar directives was the Rail Modernization Study.

2.1.2 FTA Rail Modernization Study

The Rail Modernization Study conducted between 2007 and 2009 was the first Rail Modernization study to be conducted in more than two decades. The FTA, at the request of several Senators and specific language in the 2008 Transportation

Appropriations bill, began the study in 2007 to assess the condition of the nation's largest rail transit agencies. The study included the nation's seven largest rail transit agencies in its assessment (based on rail ridership): the Chicago Transit Authority (CTA), the Massachusetts Bay Transportation Authority (MBTA), the Metropolitan Transportation Authority (MTA), the New Jersey Transit Corporation (NJ TRANSIT), the San Francisco Bay Area Rapid Transit District (BART), the Southeastern Pennsylvania Transportation Authority (SEPTA), and the Washington Metropolitan Area Transit Authority (WMATA).

2.1.2.1 Introduction

The first section of the study discusses how the FTA's own Transit Economic Requirements Model (TERM) was utilized to assess the current condition of the seven agencies' assets. The TERM uses a series of deterioration tables to rate the condition of an asset on a scale of 5 (excellent) to 1 (poor) based on factors such as age, usage, and maintenance history. The study used the TERM rating scale to define an asset as being in a "state of good repair" if it had a condition rating of 2.5 or greater. In addition, an agency whose assets had an overall average condition rating of 2.5 or greater would be considered to be in a "state of good repair". The results of the TERM analysis showed that approximately one-third of the agencies' assets were in "marginal" or "poor" condition.

2.1.2.2 Federal Funding History of Study Agencies

The second section of the Rail Modernization study discusses the federal funding history for the study agencies over the previous three Surface Transportation Bills (Intermodal Surface Transportation Efficiency Act (ISTEA), Transportation Equity Act for the 21st Century (TEA-21), and the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)), which included the

availability of federal funds for rail capital reinvestment; how much of the eligible funds received were actually applied to reinvestment; how much had been spent by the agencies on reinvestment and what share of that reinvestment was federally funded. With respect to federal funding availability, the total amount of funding available to all transit agencies for capital reinvestment had increased from \$23.6 billion under ISTEA to \$35.6 billion under SAFETEA-LU. Specifically, the amount of funding available for rail capital reinvestment for the study agencies increased from \$2.1 billion per year to \$2.9 billion per year. Of those available funds, approximately 72% were applied to rehabilitation and reinvestment, while the remainder was dedicated to preventive maintenance, expansion, and other improvements. In total, the agencies' capital rail spending increased from slightly over \$2 billion in 1992 to almost \$5 billion in 2006, with approximately 90% of the spending in 2006 dedicated toward rehabilitation and replacement. Of the rail capital funds spent in 2006, 49% of the funds came from federal sources, 28% from dedicated taxes, 20% from local sources, and 3% from the corresponding states.

2.1.2.3 Cost to Bring Study Agencies to a State of Good Repair

The third section of the study discusses in detail both how and why the TERM was used to assess the cost of bringing the seven study agencies into a "state of good repair" as defined earlier in the document (an average condition rating of 2.5 or greater) as well as the results of the assessment. The assessment included both rail and bus assets, but excluded future expansions and capacity improvements. TERM utilized the most current asset inventories for each of the study agencies to determine the individual needs of each system. The TERM assessment yielded several important results. First, the assessment estimated the current "state of good repair" (SGR) backlog for the agencies as a whole. The SGR backlog includes the immediate replacement cost for all assets that have a condition rating below 2.5, assets that have exceeded their useful life, and past-due station rehabilitations. Second, the assessment estimated the annual investment

needed for the study agencies to attain a “state of good repair” by eliminating the SGR backlog over a period of 6, 12, or 20 years (both including and excluding normal replacement needs during those time periods). Finally, the assessment estimated the annual cost of normal replacement once the SGR backlog was eliminated. The study also analyzed what would happen if federal funding and agency investment levels in rehabilitation and replacement remained constant. The study found that while, in 2006, agencies invested approximately \$5.4 billion (\$5.73 billion in 2008 dollars) to rehabilitate and replace assets, this amount fell far short of the \$8.4 billion (2008 dollars) investment needed per year to eliminate the SGR backlog in 20 years. If this difference continued, the study predicted that the study agencies’ average combined condition rating would decrease from 3.5 in 2008 to 3.19 by 2028, along with the percentage of assets exceeding their minimum useful life increasing from just over 15% in 2008 to almost 35% by 2028.

2.1.2.4 Grant Formula Modifications to Support a State of Good Repair

The fourth section of the study discusses potential changes to current federal funding programs to encourage more investment in rehabilitation and replacement, as well as how a new, temporary funding source could be created to eliminate the existing SGR backlog over several authorization cycles. The section begins by detailing the structure of the Section 5309 Fixed Guideway Modernization funding program, funding trends throughout the program’s lifetime, and discusses how well the funding levels have addressed the estimated needs of the program’s recipients. The study then discusses different potential alternatives for either modifying the existing structure of the Section 5309 program or implementing new funding structures for the program to encourage more investment in capital rehabilitation and replacement. Finally, the study discusses the possibility of creating a temporary funding source whose sole purpose is to eliminate the SGR backlog over a long period of time. It noted that such a funding source would need to be in place over several authorization periods in order to be fully implemented. The

study estimated the annual cost to eliminate the SGR backlog over a period of 6, 12, or 20 years, which also included the annual cost of normal replacement activities needed during the program's lifetime, would be between \$2.5 and \$8.3 billion (2008 dollars).

2.1.2.5 Asset Management Practices of Study Agencies

The fifth section of the study discusses the current state of asset management practices at the seven study agencies, presented in the Transit Asset Management section of this chapter.

2.1.2.6 Proposed Options

The sixth and final section of the report synthesizes the results of the study into four different options for both Congress and the FTA to consider. The first option proposes adjusting the Section 5309 Fixed Guideway Modernization funding program to favor a more balanced allocation between formula funding and the reinvestment needs of transit agencies. The second option proposes the creation of a temporary fund to eliminate the existing SGR backlog as estimated by the study and reiterates the different levels of funding required depending on the time scale of the program. The third option proposes that the FTA develop more programs to assist transit agencies in developing and/or refining their asset management practices and also reiterates the options discussed in the fifth section of the study. The fourth option proposes that the FTA create and maintain a "National Transit Capital Asset Reporting System", which would require regular reporting by all transit agencies on the condition of their assets, thereby developing a uniform set of reporting and condition assessment standards.

2.1.3 Beginning the Dialogue with Transit Agencies

During the time that the FTA was conducting the Rail Modernization study between 2007 and 2009, it also held a workshop in the summer of 2008 with several transit agencies to discuss the state of good repair of the transit industry. The results of

the workshop were presented in a report entitled “Transit State of Good Repair: Beginning the Dialogue” [6].

2.1.4 FTA Transit State of Good Repair – Beginning the Dialogue

This report introduces the FTA’s State of Good Repair (SGR) Initiative and the reasoning behind its creation. The body of the report presents the results of seven papers that were introduced and developed at a SGR workshop held by the FTA in August of 2008 with staff from fourteen different transit agencies. The papers address several issues, which include the current condition of the nation’s transit infrastructure, defining and measuring “state of good repair”, transit asset management, standards for preventive maintenance, core capacity of transit systems, alternative approaches to financing, and research needs.

2.1.4.1 The State of Good Repair Initiative

The first section of the report begins by discussing several trends in the transit industry that spurred the creation of the State of Good Repair Initiative. First, through the analysis of national transit data, the FTA estimated that roughly one-quarter of the nation’s bus and rail transit assets are in marginal or poor condition. Second, the cost to replace all assets that had exceeded their expected useful life (SGR backlog) was estimated to be approximately \$25 billion (2004 dollars), while the cost of normal replacement after the backlog had been eliminated was estimated to be between \$9 and \$11 billion annually (2004 dollars). Third, the report notes that while the number of rail systems throughout the country had increased over the years, the percentage of federal funds distributed to the nation’s oldest and largest transit operators through the FTA’s Fixed Guideway Modernization program had decreased from over 90% in 1993 to less than 70% in 2006. Fourth, the National Transportation Safety Board had become concerned for passenger and employee safety because of the deterioration of capital

assets in transit agencies. The report provides an example of this expressed concern from a derailment report published in July of 2006. Finally, the report documents several examples of local agency concerns over the condition of their assets from New York City Transit (NYCT), the MBTA, and WMATA.

The section continues by discussing the steps the FTA was currently undertaking in order to help transit agencies begin to move toward a “state of good repair.” These activities included the SGR workshop whose discussions compose the body of the report, conducting and eventually presenting the results of a Rail Modernization Study of the nation’s largest rail transit agencies, and creating a SGR working group to discuss SGR issues. The section concludes by discussing several initiatives that the FTA was considering for future implementation. These initiatives included creating an SGR roundtable to discuss solutions to common SGR issues and share best practices; development of both a working definition for “state of good repair” and tools/processes to measure it; development of a “TERM-Lite” software program for local agencies; creation of a national transit asset inventory, and research and technical assistance.

2.1.4.2 The State of Good Repair Workshop

The main body of the report begins with an introduction discussing the purpose and structure of the SGR workshop that was conducted by the FTA in August of 2008. The workshop brought together staff from the seven study agencies that were participating in the Rail Modernization Study as well as seven other smaller transit agencies to participate in seven workshop sessions. Each of the workshop sessions introduced a particular issue related to “state of good repair” and allowed for open discussion of the issue between the transit agencies’ staff and the FTA. The result of the workshop sessions were seven papers that synthesized the perspectives of several transit agencies into a general understanding of each issue as well as several questions that

needed to be addressed in the future. The introduction to the main body of the report concludes by presenting a key finding from each of the seven papers.

2.1.4.3 1st Paper – Current Condition of the Nation’s Transit Infrastructure

The first section of the first paper presents and discusses an assessment of the condition of the nation’s transit assets. The paper relies on both federal and local agency reports for its analysis, which included documents such as the biennial Condition and Performance Report to Congress and local agency Capital Improvement Program plans. Based on the asset information in these sources, the FTA’s TERM model was able to estimate the current condition of the nation’s assets as well as the level of reinvestment needed to bring all assets into a “state of good repair.” From the charts produced by the model estimates, the results show that approximately one-third of heavy rail and bus assets had either exceeded or were close to exceeding their useful lives. In addition, the estimated annual reinvestment needed to attain a “state of good repair” (defined here as replacing all assets that exceeded their useful life over the 20-year timeframe of the model) for all transit modes was approximately \$10.7 billion, which the paper notes was far above the approximately \$8.6 billion invested by all transit agencies in 2006.

The second section of the paper compares the results of the TERM analysis with condition and reinvestment needs assessments conducted by BART, CTA, MBTA, and NYCT. The comparison finds that most of the results from the TERM model are comparable with the results from the local agencies’ assessments. However, there was a significant difference between the TERM and local agencies’ estimates of the proportion of revenue vehicles exceeding their useful life. The paper explains that this was most likely because the TERM assumes the minimum useful life while local agencies normally assume expected useful life, which is longer.

The third section of the paper discusses several areas in which the condition of an asset can have an effect on transit service performance. First, in terms of operating and

maintenance costs, older assets tend to experience increased maintenance needs and therefore increasing costs. Second, as assets age they become less reliable, which can cause service disruptions if there is a failure while the asset is in service. Finally, poor infrastructure conditions (specifically track right of way conditions) can result in the need for slower speeds through these areas, which decreases performance.

The fourth section of the paper discusses the limitations of its own condition assessment at both the local and federal levels. At the local level, most agencies did not maintain comprehensive asset inventories nor did they conduct long-term state of good repair needs estimates, while only a few agencies conducted regular, detailed condition assessments. At the federal level, there was no standard condition reporting system or inventory reporting requirement for agencies (until MAP-21).

The fifth section of the paper discusses several observations from the transit agencies involved in the SGR workshop. First, several agencies were concerned that the reinvestment needs estimated by the TERM were too low because of improvements that are normally incorporated into newer assets when older assets are replaced. Second, two older rail agencies remarked that their internal estimates for SGR needs were double their current expenditures. In addition, other agencies noted that some of their operating expenses were in fact SGR-related investments. Third, most of the participating agencies noted that maintenance facilities, bridges, signals, and station amenities had the most deferred investment needs because of their low priority compared to other assets like revenue vehicles. Fourth, most agencies stressed the need to account for additional rehabilitation and replacement costs beyond the simple cost of the asset when estimating reinvestment needs. These costs include factors such as installation, design, inflation, and technological improvements. Finally, agencies noted that some reinvestment needs are more driven by technological obsolescence than condition.

The paper concludes by presenting several questions about current transit asset conditions that still need to be addressed by the industry. These include questions about

the accuracy of the condition assessments conducted by the FTA, where the greatest reinvestment needs are, how local agencies are trying to address their own needs in the light of insufficient funding, and the areas of greatest risk to transit agencies if funding levels continue to lag reinvestment needs.

2.1.4.4 2nd Paper – Defining and Measuring State of Good Repair

The second paper addresses how transit agencies should define and measure “state of good repair” as well as if the term should refer solely to asset condition or also include performance measures. In trying to define “state of good repair”, the paper first presents how several different transit agencies define the term (the CTA, Cleveland RTA, MBTA, NJ TRANSIT, NYCT, and SEPTA). The paper notes that while the definitions focus on several different concepts, most are based on the idea that “state of good repair” is a state in which all life cycle investment needs are addressed, which includes preventive maintenance, rehabilitation, and regular replacement needs. This idea becomes part of the paper’s “operational” definition of “state of good repair” along with the condition that there is no backlog of deferred capital needs. The paper also notes how the “state of good repair” concept is different from similar investment approaches such as Normal Replacement and System Improvement.

The paper continues by discussing the advantages and disadvantages of four different methods for measuring SGR as previously defined. The first method for measuring SGR is estimating the percent of assets that are in a state of good repair. The paper notes that while the result of this method is simple and easy to explain to decision makers, it does not provide much detail on the actual condition of the assets that are in SGR. The second method is estimating the percentage of useful life remaining for different asset groups (such as track) and grouping those percentages into quarter-lives. This method provides more specific asset condition information than the first method and also provides the ability to set an SGR target for either all assets or certain asset groups.

The third method is periodically grading each asset's condition based on a set of condition ratings over the life of the asset. This method provides a uniform rating scale across asset groups, which allows for condition comparisons across asset types. The fourth method is for agencies to develop condition measures that are specific to each different asset type. While this method provides great detail on the condition of a specific asset group, it does not allow for simple comparisons across asset groups. The paper questions whether the definition of SGR should be expanded to include performance-related goals in addition to condition-related goals.

The paper continues by discussing several observations made during the SGR workshop. It notes that while most of the participating agencies had already developed their own definition of SGR, they generally followed the basic idea of SGR as defined earlier in the paper. In addition, the agencies debated during the workshop over the usefulness of age, condition, and performance as measures for SGR. The agencies concluded that condition was the best measure of SGR because it utilizes the evaluations of trained experts that consider local environmental and operating factors. Age was the second-best measure because while it was more easily measured, by itself it does not incorporate the many factors than an individual condition assessment can. Finally, agencies recommended that performance not be used as a measure since it was an indirect measure of asset conditions.

The paper concludes by presenting several questions about defining and measuring SGR that still need to be addressed by the industry. These include questions about developing a uniform definition of SGR, developing uniform measurements of SGR, and how agencies are conducting asset condition assessments.

2.1.4.5 3rd Paper – Transit Asset Management

The third paper discusses transit asset management (TAM), current agency practices in TAM, and the role of TAM in achieving a “state of good repair”, presented in the Transit Asset Management section of this chapter.

2.1.4.6 4th Paper – Standards for Preventive Maintenance

The fourth paper discusses several issues with respect to preventive maintenance (PM) practices at transit agencies and these practices affect SGR.

The first section of the paper provides some background on preventive maintenance’s role in most transit agencies. In general, transit agencies’ PM programs consume a large percentage of the agencies’ total resources (i.e., budget and staff) and are normally the second-largest operating cost for agencies. The paper notes that it does not seek to increase or reduce the level of resources devoted to PM, but instead to increase the productivity of the program.

The second section of the paper discusses several strategies for improving the productivity of a PM program. The first strategy involves finding ways to increase the amount of scheduled maintenance and reducing unscheduled maintenance activities. This includes activities such as more frequent asset inspections and replacement of aging assets before they fail. The second strategy involves implementing a computerized maintenance management system for tracking maintenance activities for each asset over its lifetime. Such a system provides decision makers with data that can be analyzed to identify areas for productivity or efficiency improvement.

The third section of the paper discusses whether or not transit agencies should adopt a common set of PM standards. It notes that all transit providers have at least a basic PM program for all major asset types, including vehicles. However, there is a wide variation in how frequently inspections are conducted and what types of inspections are conducted over the life of an asset. The paper provides an example of this variation in standards from a bus condition study conducted by the FTA from 1999 to 2002. The

paper found that several important factors influenced the maintenance needs of most assets, which included level of ridership, annual hours/miles of service, climate, and make/model. Because transit agencies operate in a wide variety and scale of environments under these factors, the paper concludes that it would be difficult to develop a single set of PM standards for all agencies.

The fourth section of the paper discusses two questions about the relationship between preventive maintenance and state of good repair. First, the paper considers whether PM should be included within the definition of “state of good repair.” On this issue, the paper concludes that while PM is necessary to maintain the SGR condition, temporary lapses in PM activities does not mean a system or asset is not in a state of good repair. Second, the paper considers the impact of PM activities on asset conditions and, by extension, state of good repair. Utilizing the same bus condition study as discussed previously, the paper finds that more comprehensive and more intensive PM programs have resulted in higher asset conditions compared to less comprehensive and intensive programs.

The fifth section of the paper discussed several observations made during the SGR workshop. In general, transit agencies that participated in the workshop agreed that comprehensive PM activities could improve asset condition and useful life, thereby contributing towards attaining a state of good repair. In addition, the agencies agreed that the industry should not establish a set of standards for PM programs. However, the agencies could not come to agreement on whether PM program costs should be included in estimating SGR needs.

The paper concludes by presenting several questions regarding preventive maintenance practices and their role in achieving SGR. These include questions about if agencies are conducting the optimal level of PM activities; what strategies are available to reduce unscheduled maintenance activities; the relationship between PM activities and

SGR, and how the FTA could help agencies improve maintenance activities while reducing their cost.

2.1.4.7 5th Paper – Core Capacity of a Transit System

The fifth paper discusses several strategies for how the core capacity of a transit system can be maximized using existing infrastructure. The strategies are grouped into six categories: network, line capacity, vehicle capacity, station capacity, support capacity, and other. Network strategies include modifications to feeder bus routes, improving service on alternative routes, increased line-to-line connections, vehicle consolidation (rail vehicles), and schedule coordination. Line capacity strategies include enhanced train control technologies (such as automatic train control) and increasing line speeds (reducing curvature, etc.). Within line capacity, station dwell times can be minimized using strategies such as reducing conflicts between opposing lines through improved route configuration, improving train acceleration and braking capabilities, and implementing more efficient terminal reversing procedures. Vehicle capacity strategies include longer trains and higher-capacity cars. Station capacity strategies include matching vehicle design to the design of the station platform to maximize passenger flow, reducing platform crowding and increasing circulation, modifying station tracks and platforms, and improving station access for passengers. Support capacity strategies include increasing the capacity of the traction power system, as well as shops and rail yards, to match the needs of trains using the system. Other strategies include implementing policies to stagger work hours for employees of large businesses, implementing congestion pricing during peak periods of service, and encouraging directed development where transit demand is likely to occur in the future.

The paper continues by discussing several observations that were made during the SGR workshop. First, most agencies agreed that they needed to balance their SGR needs with their competing capacity needs. Second, several agencies mentioned that some of

their SGR investment plans included minor capacity improvements. This is primarily because aging assets are normally not replaced “in-kind”, but by assets that can carry more passengers and increase core capacity. Third, most agencies were not sure if they would benefit from more flexible federal funds between SGR and capacity improvement programs. Fourth, agencies noted that, as with SGR, a lack of funding limited their ability to meet core capacity needs.

The paper concludes by presenting several questions regarding core capacity needs and their role in achieving SGR. These include questions about how agencies balance core capacity needs with other reinvestment issues, how investment in core capacity could be balanced with system maintenance, and how federal funding should be used to maximize current core capacity.

2.1.4.8 6th Paper – Alternative Approaches to Financing

The sixth paper discusses non-traditional, alternative sources of funding that may be available to transit agencies to address SGR needs in light of the significant gap between current reinvestment levels and estimated SGR needs.

The first section of the paper discusses the strategy that the FTA encourages the most, which is the creation of public-private partnerships (PPP). While public-partnerships can be tailored to fit the needs of both the transit agency and the private sector, few agencies have experience in establishing these partnerships since they have only just begun to be implemented in the industry. The paper notes that the FTA is trying to establish educational programs for agencies as well as requesting input from agencies that do have experience in order to develop best practices. In addition, the paper lists several examples of the cost benefits of PPPs from cases at BART and the Minnesota DOT.

The second section of the paper looks at a case study of the London Underground’s (LU) PPP. It discusses the reasons behind the development of the PPP,

the responsibilities of both partners, and the details of the contracts between the LU and the three private companies it partnered with (known as Infracos). Specifically, the partnership that was created was based on a series of performance measures that the LU used to ensure that the private partners kept the system in a state of good repair. These measures included availability, capability, ambience, condition, fault reporting, major projects, and station refurbishment and modernization. Unfortunately, in only five years the partnership collapsed due to significant cost overruns by the Infracos.

The third through seventh sections of the paper describe other potential sources of funding, such as capital leasing, revenue bonds, grant anticipation notes, debt service reserves, and the Transportation Infrastructure Finance and Innovation Act (TIFIA) program.

The eighth section of the paper discusses several observations made during the SGR workshop. First, most agencies already utilized many of the alternative funding sources discussed previously to address their SGR needs. Second, all of the agencies concluded that alternative funding sources could help agencies achieve SGR in the short-term, but that agencies should carefully weigh the costs of not being in SGR versus the cost of debt financing.

The paper concludes by presenting several questions with respect to alternative funding sources and their ability to help transit agencies achieve SGR. These include questions about how agencies can maintain enough control in PPPs so that they can contract out their activities; how PPP contracts can be written to protect both public and agency interests, and if the federal government should be involved as an investor in PPPs.

2.1.4.9 7th Paper – Research Needs

The seventh paper discusses the research needs of the industry with respect to state of good repair.

The first section of the paper discusses the different research programs that the FTA oversees, which include the Transit Research Analysis Committee (TRAC), University Transportation Centers (UTC) Program, and the Transit Cooperative Research Program (TCRP).

The second section of the paper presents several important literature sources and reports related to state of good repair.

The third section of the paper discusses several research areas that are of most interest to the industry in terms of SGR. The first area is in the field of technologies or maintenance strategies that could support more reliable condition assessments and support maintenance activities. The second area involves developing better processes and/or standards for measuring “state of good repair” for different asset types and different funding scenarios. The third area of research would involve case studies to learn how different agencies (both in the U.S. and Europe) are addressing similar SGR issues and what best practices could be developed from those studies. The fourth area would involve further research into the private sector’s potential role in helping transit agencies address their SGR needs through PPPs. The second section concludes by mentioning several other future research questions for the industry.

The final section of the paper discusses several research needs that were discussed during the SGR workshop. First, agencies were supportive of the development of a “TERM-Lite” program to help estimate their SGR needs, in return for helping the FTA refine and improve the program’s capabilities. Second, agencies also supported the creation of a working group for the purpose of sharing best practices in asset management. Third, agencies were interested in learning how to develop their own maintenance management system that could be used both for tracking maintenance activities and long-term planning analyses. Finally, the agencies that already had maintenance management systems were supportive of developing a series of workshops for agencies to learn how to improve their existing systems.

2.1.5 Expanding the Scope of the Rail Modernization Study

After the results of the Rail Modernization Study were reported to Congress in 2009, the Secretary of the Department of Transportation, Ray LaHood, requested that the FTA conduct a similar, broader evaluation of the investment required to bring *all* of the nation's public transportation agencies into a state of good repair [7]. The result of this request was the National State of Good Repair Assessment, published in 2010.

2.1.6 FTA National State of Good Repair Assessment

The FTA, at the request of Ray LaHood, the Secretary of Transportation, conducted this assessment shortly after the findings of the 2009 *Rail Modernization Study* were published. This assessment's purpose was to expand the original scope of the *Rail Modernization Study* to include *all* transit agencies in the United States in order to determine the size of the SGR backlog and normal replacement (NR) needs for *all* transit agencies. The assessment is divided into three sections with a similar structure to the original *Rail Modernization Study*.

2.1.6.1 Introduction

The first section begins by discussing the expanded scope of the assessment. Unlike the 2009 *Rail Modernization Study*, the 2010 assessment included all modes, agency types, and asset types in its analysis. The assessment also provides a table showing the percentage of annual boardings, track miles, passenger stations, fleet vehicles, maintenance facilities, and agency modes that were covered by the 2009 study. While the *Rail Modernization Study* was able to capture roughly 51% of all annual boardings and track miles, it was only able to capture 2% of agency modes, 17% of maintenance facilities, 24% of fleet vehicles, and 39% of passenger stations. Like the 2009 study, the 2010 assessment utilized the FTA's TERM to determine the investment needs of the nation's transit agencies. In addition to the data provided by the original

seven study agencies from 2009 for TERM, the assessment was able to acquire data from 36 other transit agencies around the country: 16 of which replied directly to a data request from the FTA and 20 of which were reporting updated data for the TERM program. Using the data provided by the transit agencies and the definition of “state of good repair” adopted in the *Rail Modernization Study*, TERM provided an assessment of the current condition of the nation’s transit agencies. The model showed that just over a quarter of all transit assets are in marginal or poor condition. However, when the data was analyzed between bus and rail modes, approximately 41% of bus assets were in marginal or poor condition, while approximately 26% of rail assets were in the same condition. In addition, the model results showed that guideway elements made up a vast majority of the total cost of assets listed as in either marginal or poor condition.

The section concludes by discussing four different initiatives the FTA had undertaken since the *Rail Modernization Study* to provide technical and grant assistance to transit agencies that were striving to attain a state of good repair. These initiatives included an SGR Workshop held in the summer of 2008 to allow transit agencies to discuss their SGR needs and plans for addressing their backlogs in light of limited funding, the first SGR Roundtable of approximately 30 transit agencies held in the summer of 2009 to share best practices for transit asset management and reducing/maintaining the SGR backlog; the establishment of an internal SGR working group within the FTA, and the development of a discretionary grant program under the Section 5309 Bus and Bus Facilities program for the replacement or rehabilitation of bus related assets.

2.1.6.2 Cost to Bring Transit Industry to a State of Good Repair

The second section of the assessment begins by discussing the usefulness of FTA’s TERM in estimating the cost of the both the SGR backlog and normal replacement activities. As with the *Rail Modernization Study*, the model did not consider the costs of

future capacity expansion or other improvements to the nation's transit agencies in its analysis. The assessment noted that this exclusion, in addition to the use of constant dollars (i.e. no inflation), might have introduced a downward bias into the estimations made by the model. Using a condition rating of 2.5 or higher as the definition for an asset being considered in a "state of good repair", the model showed that the SGR backlog was approximately \$77.7 billion while the annual normal cost of replacement (assuming no backlog) was approximately \$14.4 billion (both figures in 2009 dollars). The model also estimated the annual investment needed to eliminate the nation's SGR backlog for periods of 6, 12, and 20 years, both including and excluding normal replacement costs. The assessment then notes that the nation invested between \$12 and \$13 billion in replacing, rehabilitating, and improving assets in 2006, which falls far short of the \$14.4 billion (2009 dollars) needed for just normal replacement activities. The model was then used to estimate the condition of the nation's transit assets if funding levels remained constant over the next 20 years to 2029. The model showed that the overall condition rating of all assets would decrease from approximately 3.78 in 2009 to 3.44 in 2029, while the percentage of assets exceeded their expected useful life increasing from 17% to almost 30% in 2029.

2.1.6.3 Transit Asset Management Practices

The third and final section of the report, presented in the Transit Asset Management section of this chapter, discusses the transit asset management practices of the 16 agencies that provided asset inventory data for the 2010 assessment as well as the original seven study agencies of the 2009 *Rail Modernization Study*.

2.1.7 An Individual Agency's SGR Assessment

Before efforts were begun at the federal level to address the issue of state of good repair in the transit industry, one agency had already conducted an assessment of its own

state of good repair needs in 2006. The agency was the Massachusetts Bay Transportation Authority, and its assessment was simply entitled the MBTA State of Good Repair Report [8].

2.1.8 MBTA State of Good Repair Report

This report was developed by the MBTA to discuss the capital challenges the agency faces as a combination of past rapid expansions and aging infrastructure reaching key rehabilitation and/or replacement milestones, what the agency has done to address those challenges, and what issues remain for the future.

2.1.8.1 Defining the System

The first section of the report briefly characterizes the MBTA system. The MBTA serves approximately 1.1 million passengers per day via a combination of bus, rapid transit, bus rapid transit, light rail streetcars, trackless trolleys, commuter rail, ferries, and paratransit vehicles. Some sections of infrastructure in the system are over 100 years old. The agency estimated that the cost to replace all of its assets over a 20-year period is \$12.4 billion.

2.1.8.2 Setting the Stage

The second section of the report discusses major system expansions that have occurred over the past thirty years. As a result of the 1973 Highway Act's Interstate Transfer program, which allowed state and local agencies to utilize Federal Highway Funds for transit projects, the system experienced significant growth and renewal from the 1970s to the 1990s. The entire vehicle fleet was replaced or renewed during this time period, extensions were made to the Orange and Red heavy rail lines, the Silver Line was constructed and extended, and the commuter rail system was established and expanded. As a result, ridership on the system has increased over the years. However, the majority of the infrastructure and assets that were built or acquired under these programs have

begun to reach the point in their service lives when rehabilitation or replacement becomes necessary. Unfortunately, funding for such activities has become much more limited and competitive at both the federal and local levels.

2.1.8.3 Recognizing the Problem

The third section of the report goes into more detail about the capital funding issue that the agency faces. The report provides a chart of annual capital expenditures over a 20-year period from 1979 to 1999, which shows that while there has been significant variation in the level of capital expenditures, over time the average level of expenditure has decreased. Meanwhile, the total stock of infrastructure that the MBTA is responsible for maintaining in a state of good repair and ridership on the system have increased over the same time period. While the agency's *Funding Forward* program provides it with a dedicated funding source that has allowed the agency to balance its budget and fund its capital program, the funding program limits the agency's ability to take on additional debt. Therefore, the agency is unable to perform additional expansion or enhancement without threatening its financial stability or the ability of its capital program to keep assets in a state of good repair. As a result, the agency currently focuses most of its resources on maintaining the existing system.

2.1.8.4 Meeting the Challenge

The fourth section of the report discusses how the MBTA has addressed the capital funding issues it faces with respect to maintaining its assets in a state of good repair. The agency began its *State of Good Repair Study* in 1999, which assessed the current condition of the agency's capital assets and the resources needed to bring them into a state of good repair. As part of the study, the *State of Good Repair Database* was developed to inventory all of the capital assets in the study and assign each asset a replacement value and "useful life" time value after which it should be replaced. This

database was used to estimate the annual level of investment needed to maintain the system in its current state of repair. In addition, the database estimated the overall size of the “backlog”, which consists of all assets that have exceeded their useful life and should be replaced or rehabilitated, to be approximately \$2.7 billion in 2006. The study then looked at four different capital funding scenarios and how they would impact the SGR backlog over a 20-year period.

The first scenario considered capital funding to be unlimited. Under this scenario, it would take approximately seven years to completely eliminate both the current backlog and additional capital needs during the same time period using an annual investment of \$4.8 billion.

The second scenario considered what would happen if funding levels remained the same over time, at the time approximately \$410 million annually. Under this scenario, the SGR backlog would increase to almost \$4 billion, while the degradation in the condition of the system would most likely result in reduced ridership.

The third scenario considered what level of funding would be required to maintain the SGR backlog at its 2006 level. The study found that an annual capital investment of \$470 million would allow the agency to maintain the SGR backlog.

The final scenario considered what level of investment would be required to completely eliminate the SGR backlog and additional capital needs over a 20-year period. The study found that an annual capital investment of \$620 million would be required to eliminate the backlog over 20 years.

2.1.8.5 Moving Forward

The final section of the report discusses how the agency plans to address future challenges to maintaining its assets in a state of good repair. Since the agency does not have sufficient capital funding to replace all of its assets at the end of their useful lives, it utilizes proactive maintenance measures in order to safely operate its assets beyond their

useful lives. However, as assets continue to age beyond their useful lives, they become a greater risk for malfunction or failure, which can result in disruptions to service, loss of ridership, and increased operating costs. With regards to system expansion, the agency will only undertake such projects if they are prudent, cost-effective, and do not reduce the resources already devoted to maintaining a state of good repair. The report notes that, as a result of the agency's focus on investing in its existing system, the percentage of funds devoted to SGR activities has increased from around 65% in 1993 to over 90% in 2007. However, as mentioned earlier in the report, the current level of capital funding is not sufficient to maintain the current SGR backlog over the long term and is far below the level required to eliminate the backlog over the next 20 years.

2.2 Transit Asset Management

2.2.1 Introduction

The material in this section is reported from the following document: Task 3: Draft Technical Memorandum – Addressing Climate Changes and Hazards using MARTA's Asset Management Program [9].

Asset Management is defined as a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision-making based upon quality information and well-defined objectives [10]:

“Transportation Asset Management is a strategic and systematic process of operating, maintaining, improving and expanding physical assets effectively throughout their life cycle. It focuses on business and engineering practices for resource allocation and utilization, with the

objective of better decision-making based upon quality information and well defined objectives.”

Public Transit Asset Management Systems ideally use quality inventory and condition data, and well-defined objectives to provide a systematic process for improving resource allocation decision-making. Maintaining transit systems in a state of good repair is critically important to maintaining and improving the social quality of life and local, regional and national economic competitiveness. SGR may be defined as a state that results from the application of asset management concepts in which a transit agency maintains its physical assets according to a policy that minimizes asset life cycle costs while avoiding negative impacts to transit service. It involves the following [3]:

maintaining an agency’s rolling stock and infrastructure as needed to meet a certain level of service (e.g., avoiding slow zones on a rail system); performing maintenance, repair, rehabilitation and renewal according to agency policy (e.g., replacing buses according to a set time interval); and reducing or eliminating an agency’s backlog of unmet needs.

The general asset management process in transit agencies involves the following [3]: collecting inventory and condition data for rolling stock and infrastructure; establishing a lifecycle policy for system preservation, including maintenance repair, rehabilitation and renewal activities, and modeling application of the policy on physical assets; and developing alternative capital programming scenarios that use the above steps together with projections of agency funding to characterize predicted future conditions and maximize the effectiveness of agency investments.

Figure 2 depicts the general asset management process for public transit agencies. Each step of this process offers opportunities for integrating climate change considerations in the context of the existing decision support framework of a transit agency.

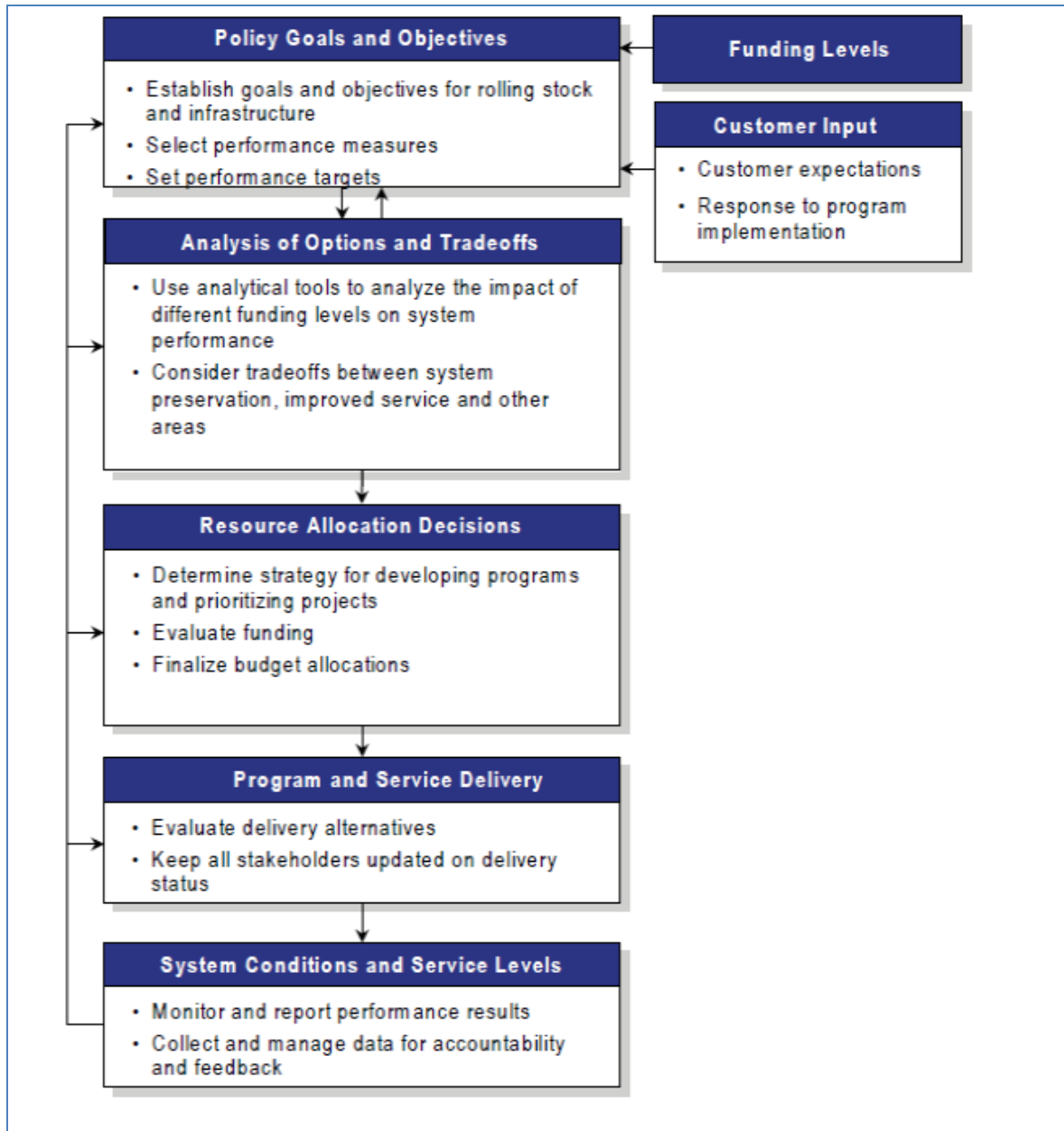


Figure 2. Transit Asset Management Process [3]

While the FTA’s State of Good Repair Initiative efforts have brought attention to the need to address the aging condition of the nation’s public transportation assets, agencies have begun to develop and implement their TAM systems. Three of the documents already referenced as part of this review contained sections that specifically address transit asset management.

2.2.2 MAP-21 and Transit Asset Management

The material in this section is also reported from the following document: Task 3: Draft Technical Memorandum – Addressing Climate Changes and Hazards using MARTA’s Asset Management Program [9].

Section 5326 of the 2012 reauthorization of the national surface transportation law, MAP-21, establishes new requirements for transit asset management by the Federal Transit Administration’s grantees as well as new reporting requirements to promote accountability. Indeed, the goal of improved transit asset management is to implement a strategic approach for assessing needs and prioritizing investments for bringing the nation’s public transit systems into a state of good repair. MAP-21 calls for a national transit asset management system which (i) defines the state of good repair; (ii) sets objective standards for measuring the condition of capital assets (including equipment, rolling stock, infrastructure, and facilities); and (iii) establishes performance measures for state of good repair, under which all FTA grantees will be required to set targets. In addition, FTA grantees are required to develop asset management plans that include, at a minimum (i) capital asset inventories and condition assessments, and (ii) investment prioritization. Each grantee would also be required to report on (i) system condition; (ii) any change in condition since the last report; (iii) targets set under the designated performance measures; and (iv) progress toward meeting those targets [11].

The MAP-21 requirements for Transit Asset Management indicate that Transit Asset Management Systems that are not at the required level of maturity will undergo developments to meet the requirements [11]. In the context of the MAP-21 requirements for transit asset management, there are several opportunities to proactively develop or modify transit asset management systems to address climate change considerations, as they are being developed to address SGR considerations. It also implies that climate change considerations are more likely to be considered progressively over time with the development or enhancement of asset management programs/systems, and project

prioritization features of AMS may include climate change considerations as one among multiple other important criteria for decision-making. However, it also opens the door for agencies to take leadership in identifying potentially high-severity, high-impact scenarios, identifying alternative sources of funding, and developing shorter-term strategies for addressing these scenarios proactively and preemptively.

2.2.3 Paper from FTA Transit State of Good Repair – Beginning the Dialogue

The third paper that was developed as part of the FTA’s State of Good Repair workshop in August of 2008 discusses transit asset management, current agency practices in TAM, and the role of TAM in achieving a “state of good repair” [6].

2.2.3.1 Transit Asset Management Defined

The paper’s first section begins by defining the concept Transportation Asset Management using the definition adopted by the American Association of State Highway Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and several state Departments of Transportation (DOTs) (see above). In addition, the paper notes that compared to traditional practices (e.g. “worst first” prioritization), asset management seeks to invest limited resources based on the merit of the different and competing needs of the organization.

2.2.3.2 The Transit Asset Management Framework

The second section of the paper introduces and discusses the basic components of a functioning transportation asset management program and how they relate to the state of good repair objective for a transit agency. These components include goals and objectives, asset inventories, condition assessment processes, decision support tools, alternatives and tradeoff analyses, decision-making, and measurements of performance.

2.2.3.3 The State of the Practice

The third section of the paper discusses several current asset management practices in the transit industry. First, it notes that most agencies have begun using maintenance management systems to track maintenance activities for their assets, though these systems normally do not contain information on all assets maintained by the agency. Second, the capital investment planning process involves engineering staff from each department developing their own estimate of needs, which are then brought together and prioritized based on the goals of the agency. While this process is conceptually consistent with the TAM structure discussed in the paper, many of these processes are informal or implicit in nature and needs may not always be prioritized objectively and strategically by decision-makers. Third, several major rail transit agencies have begun to conduct comprehensive condition assessments of their systems. However, because these assessments are conducted only once every few years, the condition data is not updated as continuously as an ideal TAM program. Fourth, only a few transit agencies have developed decision-support tools to assist decision-makers in assessing the capital reinvestment needs of their systems, most notably the MBTA, Chicago RTA, Illinois DOT, and FTA. Fifth, few transit agencies have developed comprehensive asset inventories that are designed for the purpose of asset management. Sixth, while many transit agencies utilize informal processes to prioritize investments, few have established an objective and explicit prioritization process. Finally, while many state DOTs have begun to digitally link their asset inventories, condition assessments, and other related asset databases into one system, very few transit agencies have even begun this process.

2.2.3.4 What can Agencies Learn from Transit Asset Management?

The fourth section of the paper discusses what transit agencies could learn from implementing proper asset management programs. An asset management program provides more reliable information to decision makers about the condition of the agency's assets, the level of investment required to either improve or maintain their

current condition, and how different levels of funding can impact asset conditions over time. The paper presents an example of how an effective transit asset management program can show how different funding scenarios would impact an agency's SGR backlog so that decision makers can best choose how to spend the agency's constrained funds. The example presents several charts that show what would occur under each of four funding scenarios: unconstrained, maintaining current funding levels, maintain current asset conditions, and eliminating the backlog in 20 years.

2.2.3.5 Limitations of Transit Asset Management

The fifth section of the paper discusses the limitations of asset management programs. While proper asset management is able to effectively prioritize limited funds to different and competing agency needs, it is not designed to increase the amount of resources available for investment. However, asset management provides agencies with the information they need to objectively justify their investment decisions, which can result in more cost-effective decisions that help to increase funding availability indirectly.

2.2.3.6 Observations from the SGR Workshop

The sixth section of the report discusses several observations that were made during the SGR workshop. First, many large transit agencies have fully developed asset inventories that are designed for use in an asset management program. However, few of these agencies have directly analyzed their inventories to determine their long-term reinvestment needs, while most have focused on their short-term capital improvement programs. Second, investment prioritization at many agencies is still an informal and implicit process, and the process can vary based on the agency. Some agencies focus on "mission critical" assets more than other assets, while other agencies use a negotiation process between departments, while others simply use historical funding levels as a guide for the proper investment allocation. Finally, few agencies utilize decision support tools

to estimate their reinvestment needs. However, many agencies that did not have decision support tools were interested in learning more about how to develop their own.

2.2.3.7 Remaining Questions

The paper concludes by presenting several questions about asset management and its role in SGR that still need to be addressed by the industry. These include questions about how transit agencies define “asset management,” how many agencies have implemented the various components of an asset management program, and what process agencies use to prioritize limited investment funds.

2.2.4 Section from FTA Rail Modernization Study

The fifth section of the FTA’s Rail Modernization Study discusses the current state of asset management practices at the seven study agencies [5]. It also begins by providing the definition for asset management that is used by AASHTO and the FHWA as a guide for how asset management should be defined for transit agencies (see above). The study notes that achieving and maintaining a state of good repair is only one of many other valid, competing objectives for many transit agencies.

Next, a general model is presented on how transportation asset management should be structured. Four important components of the model are identified as being most important to transit agencies trying to achieve a state of good repair: asset inventories, asset condition assessments, decision support tools/processes, and investment prioritization processes. The study proceeds to explain what each of the four components should be and what current practices the study agencies are using with regards to the specific component. For asset inventories, all seven of the study agencies had developed and/or were in the process of refining their asset inventories for capital planning purposes. However, the level of detailed data stored in the system varied greatly among the study agencies. For asset condition assessments, only three of the study agencies had

committed to perform regular assessments, while two other agencies had conducted assessments in the past but had no plans to conduct another assessment in the future. For decision support tools, only one agency (the MBTA) had developed its own tool, known as the “SGR Database” tool, which allowed it to determine both unconstrained needs and constrained priorities for reinvestment. For investment prioritization, most of the study agencies did not utilize an explicit process for determining how best to spend limited reinvestment funds. Most agencies utilized a variety of informal processes to prioritize funds, which included “mission critical” assets first, safety first, multi-factor prioritization, coordinated installation efficiency, historical funding levels, and “steady state” prioritization.

The section concludes by noting that while the transit industry has fallen behind the rest of the transportation industry in developing proper asset management practices, the FTA has several options available to assist transit agencies. These options include providing more technical guidance to agencies, developing asset management working groups to share best practices, providing grant incentives, developing the “TERM-Lite” model for local and state agencies, and creating a national transit asset inventory.

2.2.5 Section from FTA National State of Good Repair Assessment

The third and final section of the FTA National State of Good Repair Assessment discusses the transit asset management practices of the sixteen agencies that provided asset inventory data for the assessment as well as the original seven study agencies of the *2009 Rail Modernization Study* [7].

The section begins by defining what information is contained within and what data sources contribute to a capital planning asset inventory. A capital planning asset inventory normally contains both inventory data such as the asset type, location, procurement date and attribute data such as maintenance/rehabilitation history, condition, replacement cost, and expected remaining useful life. This data can be collected from

three different sources: condition assessments, fixed asset ledgers, and Computerized Maintenance Management Systems (CMMS). The section describes each of the data sources as well as the advantages and disadvantages of using each for capital asset inventory purposes.

The section continues by discussing the current transit asset management practices of the 23 agencies with respect to the development of capital planning asset inventories, regular asset condition assessments, decision support tools and processes, and investment prioritization. Unfortunately, the assessment found that only one of the additional 16 agencies had developed an asset inventory specifically for capital planning purposes. However, nearly all of the agencies had either begun the process for developing such an inventory or had recognized the need for such an inventory and expressed interest in what the best implementation strategies were. In addition, the assessment noted that each of the sixteen additional agencies utilized a combination of the three data sources mentioned previously for their asset inventory data: fixed asset ledgers, engineering condition assessments, and CMMS. With regards to condition assessments, only three of the additional 16 agencies had committed to conducting regular condition assessments of their assets. As for decision support tools, only one agency out of the twenty-three had a decision support tool in place to provide objective capital planning analyses. Finally, while all agencies utilized different informal approaches to prioritizing capital investments (previously mentioned in the 2009 study and reiterated in this assessment), only two of the 23 agencies had developed and utilized an objective, multi-factor scoring process to assist investment prioritization.

The section concludes by discussing several activities that the FTA has undertaken or already begun since the *Rail Modernization Study*. These activities include developing a one-day course on transit asset management to provide enhanced technical guidance to transit agencies, establishing working groups within the transit industry to discuss state of good repair issues and best practices, providing grant incentives to

encourage the development of sound asset management practices, developing a “TERM-Lite” program for local agencies to analyze their own SGR backlog and constrained funding scenarios, developing a national transit asset inventory to keep track of the condition of the nation’s transit assets, and the development of an asset management initiative (provided through language in the 2010 DOT appropriations bill) to further encourage the sound management and improvement of the nation’s transit infrastructure.

2.2.6 An In-Depth Review of TAM and Current Practice

While the above portions of documents discuss the state of the transit asset management practice in a general sense, the FTA completed a much more comprehensive review of the practice in 2010 [3]. This report sought to specifically review the state of the transit asset management practice, which included a literature review of the practice as well as several case studies of domestic transit agencies, international transit agencies, and two domestic state transportation departments.

2.2.7 FTA Transit Asset Management Practices – A National and International Review

The primary purpose of this paper was to report on current transit asset management practices in the transit industry by conducting case studies of six transit agencies from the United States and three agencies from other countries. The report also conducted case studies of two state DOTs’ asset management practices.

2.2.7.1 Background

The first section of the report begins by providing background information on the topic of transit asset management, what activities the FTA had conducted thus far, and the objectives of the report. As a result of its federal mandate to improve public transportation systems in the United States, the FTA had begun to address the issue of achieving and maintaining a state of good repair in the industry. Transit asset

management has been identified as a way for transit agencies to work towards achieving and maintaining a SGR condition. The FTA had hosted a two-day workshop for staff from fourteen different transit agencies in August of 2008, followed up by a larger SGR roundtable with 40 representatives from the industry in July of 2009. The eleven agencies that were used as case studies for the report were selected on the basis of them having a diverse profile of different agency sizes and geographic locations, with an emphasis on agencies that had not already been contacted for previous FTA studies. In addition, the three international transit agencies were selected on the basis of how well their experiences would be relatable to agencies in the United States.

The section continues by discussing how “state of good repair” should be defined in the context of asset management. First, the report summarizes the definitions provided by the agencies that participated in the July 2009 SGR roundtable into three general concepts that they seemed to follow: maintaining assets in order to meet a certain level of service; performing maintenance and capital investment activities according to agency policy, and reducing the agency’s capital backlog. Second, the report notes that AASHTO had developed a Transportation Asset Management Guide for state DOTs that defined asset management more broadly. The report presents the asset management program framework from the Guide.

The section concludes by providing a definition for SGR in the context of asset management as well as a definition of an ideal asset management system. From the report’s perspective, for a transit agency to evaluate its condition with respect to SGR, it requires an asset management program. Furthermore, the asset management program must periodically collect inventory and condition data for the assets the agency owns and operates, establish a set of life-cycle policies for maintenance, repair, rehabilitation, and replacement of its assets, and develop a capital planning process that considers multiple alternative investment scenarios. An ideal asset management program should perform several functions: store a complete asset inventory, record condition and performance

data on the inventory, identify deficiencies in assets, provide decision support capabilities for decision makers, track maintenance work and capital projects, and have monitoring and reporting capabilities.

2.2.7.2 Literature Review

The second section of the report details the literature review that was conducted as part of the report's purpose of exploring current asset management practices in the transit industry. The report utilizes a variety of literature sources, which include articles from the Transportation Research Board (TRB) and TCRP. The literature is divided into three groups: FTA publications, SGR practices, and models and frameworks.

The report finds three FTA publications that discussed SGR analysis and/or transit asset management. The first publication is *Transit State of Good Repair: Beginning the Dialogue*, a paper that has been discussed earlier in this literature review. The report summarizes the findings from each of the seven papers that were developed as part of the FTA's SGR workshop conducted in the summer of 2008. The second publication is *Useful Life of Transit Buses and Vans*. The purpose of this paper is to evaluate the FTA's policy on bus minimum useful service life. It includes interviews with bus transit operators, conducting engineering analyses on buses, and conducting an economic analysis. From these analyses, the paper makes several conclusions regarding the FTA's policy. First, the paper recommends that the FTA maintain its policy on bus minimum useful service life, but also to continue to review the policy over time as bus technology improved. Second, the paper finds that retirement ages generally exceeded the FTA minimums primarily due to financial constraints, not policy. Third, the engineering analyses find that the life of the bus is primarily dependent on the life of the bus structure. Fourth, the economic analysis finds that the optimal replacement window for buses was at or later than the FTA minimums. The third publication was the *Rail Modernization Study* conducted in 2008, also discussed earlier in this review. This report estimates the

SGR needs (backlog and normal replacement) for the nation's seven largest rail transit agencies.

The second section continues by summarizing ten publications created by eight different transit agencies that detail best practices in use for SGR analysis and/or transit asset management.

The first publication is *Caltrain Laying Solid Foundation*, which describes the actions taken by Caltrain to maintain the system in a SGR. These actions included developing a robust asset inventory and maintenance tracking system, a numeric condition rating system for assets, and a schedule for condition assessments.

The second and third publications are *The View from the Subway (Bus, Railroad, Bridge and Tunnel) – The Challenges of Maintaining and Operating a 100(+) Year Old System* and *Going Your Own Way*, both produced by the New York MTA. The first paper discusses the challenges that the MTA faces in maintaining an old rail transit system as well as what progress the agency has made towards attaining a SGR. The MTA's Metro-North Railroad (MNR) produced the second publication. This paper details the MNR's plans for replacing its aging vehicle fleet as well as other SGR projects, including station rehabilitations and maintenance yard expansions.

The fourth and fifth publications were produced by the MARTA and are titled *A Middle-Aged System: Metropolitan Atlanta, Georgia, Rapid Transit Authority's Transit Asset Management* and *Sustaining a Successful Transit System through its Mid-Life*. The first paper describes a presentation given at the TRB 6th National Conference on Transportation Asset Management on MARTA's transit asset management process. As part of developing a Capital Improvement Plan to maintain a SGR, MARTA conducted a condition assessment of its assets, estimated their remaining useful life, and projected capital needs for those assets over the next 40 years. The second paper describes in detail the actions taken for the condition assessment of MARTA's assets. Actions taken include developing an asset breakdown structure (ABS), performing condition assessments on a

sample of assets utilizing a 5-point rating scale, estimating the condition of remaining assets based on other condition data, estimating capital needs over the next 40 years, and developing a capital investment plan for that time period.

NJ TRANSIT produced the sixth publication, called Fix-it Central. The paper describes the impact of the new Meadows Maintenance Complex on NJ TRANSIT's ability to operate and maintain its fleet by relocating different shops from aging facilities into a centralized maintenance facility.

The seventh publication was produced by the Port Authority of New York and New Jersey (PANYNJ) and is titled *A Mature System: Port Authority of New York and Jersey's Maintenance Management Improvement Program*. This paper discusses the PANYNJ's perspective on asset management issues and challenges as well as the Authority's condition assessment approach, performance measures, and work process improvements.

The eighth publication was produced by the CTA and titled *The Framework for a Regional Transit Asset Management System*. It describes the CTA's implementation of the Regional Transit Asset Management System (RTAMS), which in its initial phase provided summary information on assets as well as operating statistics and planned projects. The paper also mentions that future phases of RTAMS will include integration with the CTA's condition assessment protocols, which utilize a 5-point rating scale based on a set of decay curves.

The ninth publication was developed by SEPTA and is titled *Use of Statistical Process Control in Bus Fleet Maintenance at SEPTA*. The paper describes that while SEPTA utilized a two-part inspection procedure for all of its buses, it did not utilize the data gathered from different inspections to improve maintenance processes. The implementation of Statistical Process Control (SPC) allowed SEPTA to track and identify bus defects over time, which allowed SEPTA to better monitor the quality of their maintenance processes.

The tenth publication was produced by WMATA and is titled *Sustaining Washington Metro: Meeting the Twin Challenges of Aging and Growing Pains*. The paper describes WMATA efforts to maintain a SGR, which involves setting and following useful life, rehabilitation, and replacement policies, conducting capital needs assessments for facilities and auxiliary equipment, and establishing measures for achieving SGR.

The second section of the report concludes by discussing several models/strategies for estimating SGR needs as well as several conceptual frameworks for transit asset management (six references in total).

The first model discussed is the FTA's TERM. The model is used to support FTA's reports such as the biannual *Report to Congress on the Conditions and Performance of the Nation's Highways, Bridges, and Transit* (C&P Report) and the *Rail Modernization Study*. For the C&P Report, the model analyzes asset conditions under four different investment scenarios: maintain asset conditions, maintain performance, improve conditions, and improve performance. While the model is composed of four different modules, the report focuses its discussion on the Asset Rehabilitation and Replacement Module. This module estimates the cost required to maintain assets at their current condition. In order to accomplish this, the module rates each asset's condition on a 5-point scale by utilizing a set of decay curves and the age of the asset being rated. Based on the condition level at which assets should be replaced, the module calculates all of the costs to maintain that condition over a 20-year period.

The second model is described in a paper titled *A Rural Transit Asset Management System*, which was developed by the University Transportation Center for Alabama for the Alabama Department of Transportation (ALDOT). The model was developed to help ALDOT manage FTA grants for rural transit agencies, which included a database inventory on all of the vehicles that had been purchased through one of the FTA's grant programs. The database also stored information on the vehicle's age and

condition, which was assessed by ALDOT using a 5-point scale based on several factors such as running condition, exterior condition, and mileage. Using the condition data provided from these assessments, the model utilized a simple linear regression model to estimate the future condition of the vehicles, thereby providing a schedule for replacement over time.

The third model is described in a presentation titled *Asset Management and Preventive Maintenance: Setting Priorities to Improve Efficiency*. The model was developed for the MBTA to estimate the needs of the system, cost to maintain a SGR, condition of the system if investment levels remained constant, and cost to eliminate the SGR backlog in 20 years. The model also takes candidate capital investment projects input by the user and scores them based on factors such as operational impact and cost-effectiveness. The projects are ranked and then scheduled using a simulated project selection process.

The fourth model is described in a paper developed for TRB titled *An Asset Management Strategy for State DOTs to Meet Long-Term Transit Fleet Needs*. The paper proposes a two-step asset management process that state DOTs could use to prioritize and allocate funds to their constituent transit agencies. The first step of the process involves utilizing a model that attempts to minimize the fleet life of buses that have exceeded the FTA's minimum useful service life standards within the constraints of available budget and required fleet size. The result of the first model is an optimal allocation of available resources between replacement, rehabilitation, and remanufacturing. The second step of the process utilizes a second model to optimally allocate the available resources output in the first model to the state DOTs' constituent transit agencies. The model allocates funds based on maximizing the remaining useful life of each agency's fleet. The paper compares this two-step process to the traditional DOT process, which involves replacing a portion of buses that have exceeded their minimum useful service life within annual budget constraints. By implementing the two-step process for the entire fleet of medium-

sized buses in Michigan, the paper found that there were significant benefits over the traditional state DOT process.

The fifth strategy is described in a paper developed for the TRB titled *Decision-Making Modeling for Rural and Small Urban Transit Management*. The paper describes a strategy for rural and small urban transit agencies that involved the use of an Ordered Probit Model (OPM) that would predict the probability of a vehicle's future condition based on variables such as maintenance and age. The condition probabilities generated by the OPM are used as the inputs for an optimization module that estimates an optimal maintenance program for either an individual vehicle or a group of vehicles.

The first of three frameworks reviewed by the report was described in a paper for TCRP titled *Guidelines for Development of Public Transportation Facilities and Equipment Management Systems*. The three basic components of a Public Transportation Facilities and Equipment Management System (PTMS) are data collection and system monitoring, identification and evaluation of proposed strategies and projects, and implementation of said projects. The paper discusses how state agencies can implement PTMSs that follow federal regulations for PTMSs within Transportation Management Areas (TMA) while also serving the unique needs of the agencies. Finally, the paper notes that the primary use of the PTMS is as a decision support and planning tool for state agencies and Metropolitan Planning Organizations (MPO) and not as an asset management system for transit agencies.

The second framework, Asset Management Program Learning Environment (AMPLE), is described in the paper *Applying the Lessons Learned in Asset Management Around the World to the Development of the AMPLE Tool*. The AMPLE tool is used to help guide agencies in their development of asset management processes. The tool includes seven modules on the different aspects of asset management such as gap analysis tools, implementation, and improvement planning.

The third framework is described in a paper titled *Development of Asset Management Evaluation Framework in Rail Environment: London Underground Public-Private Partnership*. The framework was developed by Lloyd's Register (LR) for independently evaluating the performance of the Infracos established by the LU's PPP contract. The paper developed an ideal asset management framework based on a global investigation of asset management practices. The result was 12 different asset management components (divided into process and enabling elements) that could be used to evaluate the performance of an agency's asset management system, as well as evaluation tables that could assess the maturity of the system. Process elements included risk management, planning, and delivery, while enabling elements included active leadership, competency, and communications. The evaluation tables would rate an agency's success in each element on a scale of 0 to 5.

2.2.7.3 Case Studies

The third section of the report begins by discussing which transit agencies were selected for case studies and the methodology for collecting information from each. As mentioned previously, 11 agencies were studied as part of the report, which included six U.S. agencies, three international agencies, and two state DOTs. The case studies involved both phone interviews with agency staff and reviewing documents published by the agency. The report also discusses the process used for conducting phone interviews with each transit agency (only published documents were used in the case studies of the two state DOTs). The case studies are divided into three sections based on the groups mentioned above: U.S. transit agencies, international transit agencies, and state DOTs. Each study is composed of three sections: background, practice overview, and noteworthy aspects.

The first group of case studies considers six different U.S. transit agencies. The first agency studied was Chapel Hill Transit, which is based in North Carolina and has an

annual ridership of approximately 5.7 million passengers. The report finds that an important goal for the agency was the maintenance of its vehicles and facilities. In addition, “state of good repair” was defined by the agency as ensuring that the system remained functional and operational while also being maintained in a good condition. The report finds that the agency’s strategy for addressing state of good repair was composed of several primary components: establishing maintenance policies tailored to each new fleet of buses, replacing bus fleets as close to FTA guidelines as possible under budget restraints, and utilizing an inventory and maintenance tracking program (TRANSMAN). The agency faced two challenges with respect to achieving a SGR: uncertainty about future funding sources and the unknown impact of new regulations such as the 2010 emissions requirements. The report noted that noteworthy aspects of the agency’s transit asset management practices were its use of unique maintenance policies for each new bus fleet and experimenting with a vehicle management system for tracking fixed assets.

The second agency studied was the CTA, one of the nation’s largest transit systems with a ridership over of 525 million passengers annually. Being a larger and older system, the report noted that SGR was an important part of CTA’s operations. CTA defined SGR by four distinct standards: rail lines free of slow zones and with reliable signals; bus rehabilitations at 6 years and replacement at 12 years; rail cars rehabilitated at quarter and half-life and replacement at 25 years, and maintenance facilities replaced at 40 years (or 70 if they were rehabilitated). In addition, the CTA had developed a performance management program that utilized a comprehensive set of performance measures in order to monitor asset performance across the entire agency. Performance measures included miles between in-service failures, number of slow orders for track, and station/vehicle cleanliness. The CTA had also developed standardized procedures for inspecting its rail cars, buses, and track and assessing a condition rating using a 5-point scale similar to the one used by FTA’s TERM. In order to track its asset inventory and

maintenance activities, the CTA utilizes the Maximus Management Information System (MMIS) for its vehicles and the Infor Enterprise Asset Management (EAM) system for fixed guideways. Finally, the agency occasionally conducts 20-year needs assessments for capital planning purposes. The assessment estimates the amount of unconstrained resources that would be required to rehabilitate or replace all assets requiring such service within different periods of time. The report's noteworthy practices for the CTA include implementing a comprehensive performance management program, developing a 5-point rating scale for reporting asset conditions, and utilizing a standard approach for needs assessments.

The third agency studied was the Greater Richmond Transit Commission (GRTC), which serves the City of Richmond and Henrico and Chesterfield Counties in Virginia with an annual ridership of over 10 million. Achieving SGR was an important goal for the agency, which had been demonstrated through both the reduction of the average bus age and the securing of funding for a new maintenance facility. The agency utilizes a robust set of policies and systems to work towards achieving a SGR. Specifically, the agency developed maintenance policies for all of its vehicles and established specific milestones at 6,000-mile intervals. At the 6,000-mile interval (3,000 miles for non-revenue vehicles), preventive maintenance inspections are performed, in which oil samples are taken for analysis. The agency also uses AVM2 monitoring devices on its vehicles. Vehicles are overhauled on an as-needed basis, based partly on the oil samples taken during inspections. In addition, buses are replaced as close to the FTA's 12-year cycle based on available funding. Physical facilities are inspected on an as-needed basis, unless FTA guidelines require more routine monitoring. Finally, the agency utilizes the RTA Fleet Management System to track fleet inventory and schedule and track maintenance orders. Challenges for the agency with respect to achieving a SGR include uncertainty about future funding sources and adapting to new vehicle technologies (e.g. hybrid vehicles). The report found two noteworthy transit asset

management practices: the implementation of the AVM2 monitoring system to improve vehicle maintenance and utilizing a flexible vehicle overhaul process based on oil sample analysis.

The fourth agency studied was Metro St. Louis, which serves four counties in Missouri and Illinois (including St. Louis) with a combination of light rail, bus, and paratransit vehicles. The agency established a preventive maintenance program in 2002 for its vehicles to begin improving the condition of its system. The report finds that the program had four key components. First, the program established standards for maintaining the agency's vehicles, which included specific inspection and maintenance activities at particular time and/or mileage intervals. Second, two plans were developed: one for maintaining the agency's existing assets and another for future asset replacement. Third, the agency implemented the MAXIMUS/AssetWorks M5 program to manage its vehicle fleet, facilities, part orders, and other maintenance activities. Fourth, the agency estimates its capital needs based on the cost of recommended maintenance and replacement activities. In addition to its preventive maintenance program for vehicles, the agency performs regular inspections of its track and guideways, but does not input the data from these inspections into the M5 program. The agency has also developed a comprehensive and agency-wide performance measuring and reporting system, using measures such as mean distance between failures and number of customer complaints. The primary challenge for the agency with respect to SGR is uncertainty regard future funding (and therefore service). The report finds two noteworthy practices: the implementation of a preventive maintenance and fleet management program (M5) for its vehicles and the use of performance measures that included asset condition and performance as part of an agency-wide performance monitoring program.

The fifth agency studied was MARTA, which serves the City of Atlanta as well as Fulton and Dekalb Counties with heavy rail, bus, and paratransit vehicles and has a ridership of over 105 million passengers annually. The report found that MARTA's

definition for SGR does not include the elimination of the backlog of investment needs, but rather maintaining assets in functioning condition. By this definition, MARTA has estimated that 80 to 90 percent of its assets are in a SGR. However, because the MARTA system is near the age of replacement for many of its rail infrastructure assets, maintaining the system in a state of good repair will be a challenge for the agency. For rubber-tired vehicles (bus, paratransit, and non-revenue vehicles), MARTA has implemented maintenance and rehabilitation policies as well as a planned replacement program. In addition, MARTA has implemented an MMIS to track its asset inventory with condition data from inspections, maintenance work orders, and other inventory data. This system has been converted to the MAXIMUS/AssetWorks FA Suite, which also tracks other assets. For its rail vehicles, MARTA developed the Life-Cycle Asset Rehabilitation and Enhancement (LCARE) program, which is supported by the MMIS. The program defines a set of maintenance activities to be performed over the life of each car, but is unique in that it considers that the car is composed of a series of sub-components that have different life-cycles. Because of this subcomponent consideration during maintenance inspections, MARTA's maintenance staff was able to work with accounting and procurement staff to adjust vehicle depreciation and replacement schedules to maximize the life of its rail vehicles. For fixed assets, specifically rail, MARTA conducts regular track inspections that are stored within the MMIS. Similar to its bus maintenance program, MARTA has worked with MAXIMUS and Bentley to develop a program called OPTRAM to manage track-related information. Fixed assets other than those that are rail-related are not stored within the MMIS, but MARTA plans to eventually unite all asset data into one unified system. MARTA had conducted a condition assessment in the past in support of its Capital Improvement Program (CIP), but was performed before the implementation of the MMIS. Three noteworthy aspects of MARTA's practices are the development of the LCARE program for maximizing the life

of its rail cars, utilizing a single MMIS for managing the maintenance of both vehicles and track, and developing the OPTRAM program to manage track.

The sixth agency studied was the Metropolitan Transit Commission, which is the MPO for the San Francisco Bay Area and the designated recipient of FTA funds. The agency oversees 22 transit agencies within its jurisdiction such as BART, the San Francisco Municipal Railway (MUNI), and Caltrain that have a combined ridership of over 500 million passengers annually. As an MPO, the MTC is responsible for providing regular updates of both the Transportation Improvement Plan (TIP) and the longer-range Regional Transportation Plan (RTP). As part of its update to the RTP, the MTC developed the Regional Transit Capital Inventory (RTCI) to assess the inventory of assets managed by its constituent transit agencies as well as estimate the cost of attaining a state of good repair, which is defined by the MTC as replacing all assets at the end of their useful life. While some agencies were able to provide detailed information on their assets, others were not able to, which required the MTC to use basic cost estimates. Based on the agency's definition of SGR, age was used as a proxy for asset condition in developing the unconstrained needs estimate for the RTCI, in which assets that had exceeded their expected useful life were replaced in the first year of the RTP. From the results of the RTCI analysis, the MTC measured the overall Average Age of Assets as a Percentage of their Useful Life (AAPUL) at 75 percent (goal is 50 percent). Since the investment needs of the constituent transit agencies exceed available funds, the MTC utilizes an agreed-upon process with its constituent agencies to prioritize available funds. The report found that MTC's noteworthy practices were the integration of data from multiple agencies into a single analysis, defining asset categories and service lives for all assets, and developing a single performance measure (AAPUL) for SGR.

The second group of case studies considers three international transit agencies. The first agency was the LU – a subsidiary of Transport for London (TfL) – one of the busiest rail transit systems in the world, serving over 1 billion passengers annually. The

LU was privatized in 2003 through a contract made with three private infrastructure companies, called Infracos, which were responsible for maintaining and replacing the rail vehicles and infrastructure under their jurisdiction for a 30-year period, while the LU remained responsible for operations and oversight. Unfortunately, in only three years one of the Infracos – Metronet – went bankrupt, requiring the LU to take over two of the three contracts. The report finds that achieving a SGR is part of two of TfL’s five objectives that are stated in its annual investment plans: “ensuring current service levels are supported” and “achieving a state of good repair, addressing a backlog of maintenance or asset replacement.” The LU’s strategy for achieving a SGR was already developed in its contracts for the Infracos, which it is now responsible for. The contracts required each Infraco to develop an inventory of its assets and their condition. The contract also established standards for measuring the “residual life” of an asset and required that the overall system must have at least half of its residual life remaining at the end of the contract. In addition, adjustments to the monthly compensation of each Infraco were made based on the performance of each Infraco to measures developed by the LU. These performance measures included ambience in vehicles and stations, infrastructure availability, capability to provide service, and fault rectification. Since the LU had taken over two of the contracts, it was responsible for conducting all of the inspection, maintenance, and replacement work required in the contracts. The LU established a set of standards for maintenance based on the industry’s best practices. The LU primarily uses “Category 1 Standards” for its assets. For vehicles, this includes conducting inspections (either “light” or “heavy”) for each car for each shift. Tracks are inspected with both daily visual inspections and two-month passes with a track geometry vehicle. Asset performance under this maintenance program is reviewed every month during an Asset Performance Review Maintenance (APRM) meeting. Performance measures include mean time/distance between in-service failures and lost customer hours. In addition, the LU develops and presents an annual asset management plan to TfL that provides

recommendations for investment based on past performance and available funding sources. The plan also presents the percentage of assets within each condition category (from A to E), which is based on residual life remaining. The LU utilizes the Minicom ELLIPSE Enterprise Resource Planning System to store and track asset inventory data, condition data, and maintenance work. In addition, handheld devices used for inspection purposes are integrated with the system. Finally, the LU conducts a 10-year projection of costs based on its asset management plan as well as recommendations for allocating available funds. If the available funds were not enough to cover the cost of the recommended investments, the investments were prioritized for minimizing lost customer hours and reduced asset life. The report found that the LU's noteworthy asset management practices were the development of a comprehensive asset condition inventory; the use and measurement of lost customer hours to link maintenance to customer satisfaction, and developing an explicit asset management plan based on available resources.

The second international agency studied was the Toronto Transit Commission (TTC), which serves over 466 million passengers annually through a combination of rail, streetcar, and bus lines. Achieving SGR became a primary goal of the agency under the guidance of David Gunn after the Russell Hill accident in 1995. The accident, which was attributed to a combination of human error and failure of the subway's signaling system, killed three people and injured 36 others. The TTC reorganized its management and funding structures to focus on an SGR maintenance policy that prioritized maintenance over system expansion projects. The case study conducted by the FTA focused primarily on the TTC's subway and streetcar rail assets. The TTC has developed a comprehensive and detailed set of preventive maintenance and rehabilitation policies for its rail vehicles, track, and structures, which are based both on the manufacturer's recommendations and TTC's own experiences. For example, rail vehicles are expected to last 30 years with major rehabilitations conducted every five years. In addition, the Subway Maintenance

System (SMS) tracks all maintenance activities for rail vehicles, as well as some nonrevenue assets. The TTC also developed a comprehensive series of asset types and subtypes for making an inventory of and maintaining its track and structural assets, which dictate an asset's expected life and inspection schedule. The TTC uses three different systems to track its assets: IBM's Maximo for order tracking, Zetatech's Maintenance of Way Information System (MOWIS) for tracking rail track, and the Structures Maintenance Database (SMD) for tracking structural inspections. While the TTC conducts regular inspections of its assets as well as an annual condition assessment of all of its assets, it has not developed its own asset condition rating system. In addition, no performance measures have been developed for monitoring performance or setting SGR goals for the agency. However, the report notes that the agency conducts annual audits of all of its departments, has clear policies on accountability with regards to asset management, and occasionally updates its practices based on peer review. Based partially on its annual condition assessment, the TTC develops both a 10-year unconstrained needs forecast and a constrained maintenance plan based on the expected budget each year. The report found three noteworthy aspects of TTC's asset management practices. First, the agency expressed early leadership and continuing institutional focus on achieving and maintaining SGR. Second, the agency had developed a comprehensive and detailed structure for its asset inventory by defining asset types and subtypes. Finally, the agency had developed an explicit approach to inspection, maintenance, and information systems for its assets, particularly track and structures.

The third agency studied was the Victoria Department of Transport, which is responsible for the rail, trams, and buses within Victoria that serve over 262 million passengers per year. Similar to the London Underground, Victoria privatized its public transportation system in 1999 with the creation of five franchises. Unfortunately, like the LU's Infracos, all of the original franchises were eventually bankrupt or in significant financial distress. Therefore, in 2004 the franchises were restructured and now many

different companies own or operate different components of the public transportation network, from the land the infrastructure stands on to the ticketing systems. The agency described its general policies on asset management in a 2000 report titled *Sustaining Our Assets*. As with the London Underground's contracts with the Infracos, the purpose of the report was to establish standards for performance for the franchisees related to the maintenance of the system. In its original franchise agreements, the Victoria DOT developed a set of indices that would be measured to determine the physical condition of the transportation infrastructure, rated on a scale from 0 to 100 (100 being the best condition). The Victoria DOT conducted an initial baseline condition assessment and would conduct additional assessments every three years, while the franchisees were responsible for maintaining their assets to at least the average condition as determined by the initial assessment. Unfortunately, after several years of practice, the Victoria DOT concluded that there were several issues with this rating methodology and revised it along with the franchise agreements in 2004. Some of the issues were that the rating system was too subjective; franchisees were unable to determine the condition of their assets between condition assessments; and the methodology for the indices was simply too confusing. The revised methodology involves each franchisee developing and submitting an Asset Management Plan (AMP) to the Victoria DOT that describes how the franchisee will conduct inspections, maintenance, and quality assurance as well as establishes performance standards and response times. The franchisee is then held to the standards and policies in the approved AMP and submits an Annual Works Plan that describes any capital projects planned for the following year. In addition, the franchisee prepares and submits both a Rolling Stock Management Plan and an Annual Rolling Stock Management Plan every year, which describes the franchisees' maintenance and rehabilitation policies for each type of rolling stock. Finally, all franchisees provide quarterly performance reports to the Victoria DOT on a series of key performance indicators (KPIs) for their infrastructure and/or rolling stock. While franchisees are

responsible for maintaining an inventory of their equipment and rolling stock, the Victoria DOT developed its own asset inventory for tracking the condition of its rail infrastructure. The Victoria DOT developed this inventory by commissioning the Victorian Rail Infrastructure Survey, which collected extensive and detailed information on all of the agency's rail infrastructure assets and deposited this information into the Privatized Assets Support Systems (PASS) database. The report found three noteworthy aspects of the Victoria DOT's asset management practices. First, the agency had developed a comprehensive asset management approach that was documented through both official government policy statements and the franchise agreements. Second, the agency had significant experience in establishing condition measures for its infrastructure and rolling stock. Third, the agency had developed a comprehensive and integrated web-based inventory of its entire rail infrastructure network.

The third group of case studies looked at the asset management practices of two state DOTs. The first agency studied was the Oregon Department of Transportation (ODOT). The report found that the ODOT faced three primary challenges to maintaining their assets in a state of good repair: aging infrastructure, concentrated population growth, and limited additional state or federal funding resources. Therefore, the ODOT developed the Oregon Transportation Plan, which established priorities for maintaining or improving the agency's assets. The priorities are (from highest to lowest): protection of the existing system, improving the performance of existing highways through minor improvements, adding capacity to the existing infrastructure through major improvements, and constructing new facilities. The agency manages its assets through a variety of management systems, some of which were required by ISTEA. These systems include the Pavement Management System (PMS) for monitoring pavement conditions and future needs, Bridge Management System (BMS) for monitoring bridge conditions and future needs, Maintenance Management System (MMS) for tracking maintenance work, R2SIGN database for signage, and TransGIS for a web-based Geographic

Information System (GIS) inventory of all assets. These systems are supported by information from road and bridge inspections, which are conducted annually by the ODOT. In order to measure the agency's performance, several Key Performance Measures were developed as part of the statewide Oregon Shines initiative. The ODOT reports on its performance compared to state benchmarks on an annual basis. The report found that the three most noteworthy aspects of the ODOT's asset management practices were its emphasis on asset management concepts in its goals and objectives; using an extensive set of management systems to support asset management efforts, and establishment and reporting of Key Performance Measures across the agency.

The second group of agencies studied is referred to as the Virginia Transportation Secretariat, which includes the Virginia Department of Transportation (VDOT), the Department of Rail and Public Transit (DRPT), Virginia Port Authority (VPA), Department of Aviation (DOAV), and several other agencies that are responsible for various transportation infrastructure systems within the state of Virginia. As part of the statewide transportation plan, VTrans 2025, several asset management strategies were identified for constituent agencies to implement. These strategies included continuing the implementation of "maintenance first" policies; increasing the use of new materials, technologies, and strategies that would reduce long-term maintenance costs; continuing to develop more mature asset management systems, and reducing disruptions due to maintenance activities. For roadway assets, the VDOT developed its own asset management framework, which is comprised of several components: the Asset Management System (AMS), Pavement Management System, Bridge Management, Random Condition Assessment, Other Infrastructure Assets, Equipment Management, and Snow Removal. The AMS supports the development of the Needs-Based Budget by integrating information from the current asset inventory, Random Condition Assessments, planning, and work accomplishments. Other assets and activities, such as winter maintenance, are not handled by the AMS but are still accounted for in other ways

in the Needs-Based Budget. The VDOT eventually expects to have a fully populated asset inventory, at which point it will discontinue the use of random condition assessments to estimate the overall condition of its assets. For transit assets, the DRPT collects data on each transit agency's vehicle fleet in order to calculate the average bus age for each fleet, which is a proxy for condition. The agency has also developed the Program Guidance and Grant Evaluation System (PROGGRES) to predict future capital needs for its constituent agencies, which it will use in evaluating grant proposals from those agencies. While the initial release of PROGGRES was developed for buses, it has the capability to analyze the future needs of other transit assets, such as passenger rail vehicles, transit facilities (e.g. shops), and infrastructure (e.g. track). In order to monitor and measure the performance of the entire transportation system, the Virginia Performs initiative was developed. This program requires all agencies that are part of the Transportation Secretariat to report on their objectives and key performance measures. Specifically, the VDOT developed a performance dashboard to graphically show its performance. With respect to asset management, the VDOT uses three primary measures: percent of "nondeficient" pavement on interstate and primary roadway lane-miles, percent of lane-miles with "fair" or better ride quality, and percent of bridges not Structurally Deficient. In addition to the performance reporting required by Virginia Performs, VDOT is required by the state legislature to report biennially on the condition and performance of the surface infrastructure in Virginia, as well as report on the condition of the transportation infrastructure and measures of performance in areas such as accomplishments involving outsourcing, privatization, or downsizing. The report finds that the three most noteworthy aspects of Virginia's Transportation Secretariat were the establishment of statewide performance reporting (most notably VDOT's performance dashboard); VDOT's implementation of an approach to predicting and reporting future pavement, bridge, and maintenance needs, and the development of the PROGGRES tool for evaluating transit grants.

2.2.7.4 Conclusions

The fourth section of the report begins by providing a summary of the findings from both the literature review and case studies into two tables. The first table summarizes the findings into seven subject areas within asset management: establishing policies/goals/objectives, performance measures, asset inventory, condition assessment, maintenance policies, information systems, and scenario analysis. For each subject area, the representative existing practice is defined and examples of benchmark, state-of-the-art practices are provided from the study agencies. For example, the existing practice for maintenance policies involves establishing written policies for asset rehabilitation and replacement for vehicles and track based on time and/or mileage intervals. Benchmark practices for this subject area include MARTA's LCARE program, Chapel Hill Transit, and the GRTC, which have developed policies designed to minimize life-cycle costs and maximize asset serviceability. The second table summarizes the practices and support systems in place for the six US transit agencies in six functional areas related to asset management: inventory, inspection, identifying deficiencies, decision support, tracking work, and monitoring/reporting. For example, MARTA's asset inventory is stored in the MAXIMUS MMIS; inspection data is stored in the MMIS; deficiencies are identified manually through inspection; needs are projected externally from the MMIS; the MMIS is used to track maintenance work, while the CIP tracks capital projects; and the MMIS is used for maintenance monitoring.

The conclusion continues by providing several final observations about the state of asset management practices. First, many agencies have adopted practices that are consistent with the concept of asset management, while several have adopted practices that are considered state-of-the-art. Second, all of the agencies studied have developed an explicit and detailed approach to asset inspections and have systems to store and track inspection information. However, most inspections conducted by the study agencies are used to identify deficiencies in an asset, not assess its condition. Third, the most

commonly used measures for asset condition and performance are age, remaining useful life, or mean/time distance between failures. Fourth, while a wide variety of models have been developed for predicting future asset replacement and rehabilitation needs, such as FTA's TERM, the MBTA's SGR database, and others, most agencies do not have such a model or explicit needs identification process. Finally, most agencies use their asset management program to track inspection and maintenance performance, but not capital project performance. The report concludes by mentioning that while the transit agencies studied have begun to move toward attaining a SGR, the industry as a whole has significant room for improvement. However, the report notes that the transit industry has examples and practices to learn from both state DOT's long history of achieving SGR for highway infrastructure and international agencies' use of privatization to establish comprehensive and detailed asset management policies.

2.2.8 FTA Asset Management Guide

The FTA is currently in the process of completing an asset management guide that is designed to educate transit practitioners on asset management and how they can develop and implement their own transit asset management system [12]. Unfortunately, since the guide has not been published yet, it was not available for review at the time of this writing.

2.3 Climate Change Adaptation

2.3.1 Introduction

As transit agencies have begun to better understand the condition of their assets and to move towards achieving a state of good repair through the implementation of agency-wide asset management practices, there is one growing concern that agencies must factor into decisions regarding their assets and operations: the impact of the effects of climate change on agency assets and operations.

2.3.2 The Effects of Recent Climate Hazards on Transit Operations and Assets

Initial recovery and rebuilding cost estimates (including infrastructure repair and replacement costs) of the 2012 Super Storm Sandy have been placed in the tens of billions of dollars by the Associated Press, at once highlighting the potentially significant impacts of climate change on societies and civil infrastructure; the vulnerability of our older infrastructure systems and traditional designs to modern climate patterns; the significant financial, economic and social costs and risks associated with climate hazards particularly in the context of human life and basic infrastructure services; the opportunity to rebuild smarter after disaster events with improved designs and design standards; and the wisdom in taking a measured and systematic approach to developing infrastructure resilience with respect to modern climate patterns. Indeed, New York's Metropolitan Transit Authority (MTA), with a daily ridership of over 5 million, has referred to the impact of the Super Storm as unprecedented in the history of the nation's largest transit system [9].

2.3.3 Policy Statement from the Federal Level

The need for transit agencies to develop strategies for adapting to climate change was first expressed at the federal level in a policy statement that was issued by the FTA in 2011 in response to an executive order [13].

2.3.4 FTA Policy Statement on Climate Change Adaptation

This paper describes the FTA's new policy on incorporating climate change adaptation into its planning, operations, policies, and grant programs. The policy was adopted under the authority of Executive Order 13514 – *Federal Leadership in Environmental, Energy, and Economic Performance*, which includes direction to address climate adaptation planning.

2.3.4.1 Purpose & Background

The first section of the paper discusses several reasons behind the development and adoption of the climate adaptation policy. First, the impacts from climate change are already being felt in the United States and even with aggressive mitigation efforts, past emissions will result in the intensification of these impacts over several years. Therefore, the impacts of climate change should be addressed by both mitigation and adaptation strategies. Second, while public transportation currently serves an important role in climate change mitigation through reduced emissions and compact development patterns, the effects of climate change will put increased stress on its assets and operations. More intense rainfall, hurricanes, and storm surges make tunnels and maintenance facilities more vulnerable to flooding, while intense heat can buckle rails and cause worker and passenger safety issues. Third, since the FTA is responsible for the stewardship of taxpayer investments in public transportation infrastructure, it is imperative that the FTA increases its knowledge about climate change and the impacts to public transportation assets and operations so that they can be protected through better planning and design methods.

2.3.4.2 Process

The second section of the paper briefly describes the process that the FTA will use to integrate climate adaptation planning into its programs and operations. It will create a working group to analyze the impact of climate change on the FTA and develop strategies to incorporate climate adaptation into the agency's policies, programs, and operations. The working group will also propose organizational strategy options to senior executives. In addition, the FTA will coordinate with other agencies on common climate adaptation issues through the USDOT Center for Climate Change and the Council on Environmental Quality Communities Adaptation Working Group.

2.3.4.3 Resources

The third section of the paper notes that the FTA will utilize its discretionary funding programs and staff resources to support climate change adaptation planning. In addition, FTA's capital funding programs can be utilized to support investments that increase the resilience of assets to the effects of climate change, while planning program funds can be used for climate change vulnerability and risk assessments.

2.3.4.4 Guiding Principles

The fourth section of the paper lists the guiding principles behind the FTA's Interagency Climate Change Adaptation Task Force. These include principles such as adopting integrated approaches, using the best available science, building strong partnerships, and continuously evaluating performance.

2.3.5 Climate Change Adaptation for Transit Agencies

Not long after the FTA introduced its official policy statement on how it would incorporate climate adaptation into its existing programs, it published a report that specifically discussed how several primary effects of climate change were expected to impact transit agencies, how agencies could conduct their own climate risk assessments, what potential adaptation strategies could be used to address the climate risks, and how to implement the strategies through existing agency practices [1].

2.3.6 FTA – Flooded Bus Barns and Buckled Rails Report

The purpose of this report was to encourage and assist transit agencies to begin developing strategies for adapting to climate change by providing a transit-focused analysis of predicted climate change impacts, strategies for assessing and addressing local climate risks, and several options for implementing those strategies. The report uses several case studies to show how other transit agencies have begun the process of adapting their systems to future climate change impacts. The report is divided into six

sections: Introduction, Impacts, Climate Risk Assessments, Strategies, Implementation, and Conclusions.

2.3.6.1 Introduction

The first section of the report begins by emphasizing the importance of public transportation in America in helping commuters get to their jobs, providing disabled persons more mobility, and encouraging more efficient land use and environmental stewardship. The report notes that climate change and its impacts have not yet gotten the attention they deserve within the transit despite their potentially devastating impact to transit assets and infrastructure. Several examples of how the effects of climate change could impact transit assets are discussed, such as the buckling of rail tracks due to extreme heat. These impacts put additional stress on transit agencies that are just beginning to focus on bringing their entire portfolio of assets into a state of good repair. However, the report notes that the challenge of climate change presents an opportunity for agencies to re-evaluate their rehabilitation and replacement policies towards more climate adaptive strategies that result in assets and designs that reduce costs. While transit agencies already provide significant climate mitigation benefits, such as offering a low-emissions option to driving, many have not begun to consider how they will adapt to climate impacts that will occur in the short-term in spite of aggressive mitigation efforts.

The report references two studies that helped to advance the cause of climate change adaptation: the USDOT's *Gulf Coast Study* and the TRB's Special Report 290: *Potential Impacts of Climate Change on U.S. Transportation*. While these two studies were important in beginning to study the issue of climate change adaptation, the report finds that their broad scope did not allow for them to consider issues relevant to the transit industry. Therefore, the report intends to build upon the work already accomplished to look specifically at climate change adaptation from the transit industry's unique perspective. The report identifies three ways in which the transit industry's

perspective is unique from others: it uses a wide variety of assets and infrastructure to deliver its services, its services are most important to vulnerable groups such as the elderly and disabled, and it lacks a uniform design between different networks (unlike the Interstate system).

The section continues by discussing the FTA's role in helping constituent agencies to address climate change through grant programs for rehabilitation, replacement, construction, and planning as well as the importance of doing so. However, most agencies lack the capacity to conduct their own climate change adaptation planning. In addition, the White House's Council on Environmental Quality (CEQ) has directed all federal agencies to conduct climate adaptation planning and provided a set of guidelines for doing so. In developing the report, the FTA's research team reviewed relevant literature on climate change, adaptation, and transportation, consulted both domestic and international agencies about their experiences with climate adaptation, and conducted interviews with agency representatives, academics, and a variety of experts.

The section concludes by noting that the report does not seek to be comprehensive or definitive in addressing climate adaptation for transit agencies, but seeks to encourage transit agencies to begin to focus on addressing the issue and provide some initial information to assist them. In addition, there is an excerpt from the U.S. Global Change Research Program's (USGCRP) *Global Climate Change Impacts in the United States* that provides background to the climate change issue, a brief explanation of the similarities and differences between climate mitigation and climate adaptation (as well as some definitions), and a description of the guiding principles for adaptation excerpted from the CEQ's *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Adaptation Strategy*.

2.3.6.2 Impacts

The second section of the report begins by identifying the four primary climate change impacts that will affect public transit agencies: more intense precipitation, more frequent very hot days/heat waves, rising sea levels, and more intense hurricanes, all of which are either likely or very likely to occur within the next century. However, the report notes that the intensity of these impacts will be based mostly on the level of greenhouse gas emissions in the atmosphere; it provides a brief background on the studies that have used the various emissions scenarios developed by the IPCC. The section continues into a detailed discussion of the climate science behind and related secondary impacts for each of the four major climate change impacts.

The first major climate impact discussed is more intense precipitation. The report presents a figure from the USGCRP that displays how heavy precipitation events have increased in frequency over the past several decades. It finds that intense precipitation events have become more frequent and more intense even while, in some areas, annual precipitation has decreased. Furthermore, this trend is expected to continue as the air continues to warm, thereby increasing its ability to hold water vapor. One of the events that are influenced by more intense precipitation is flooding. The report presents two examples from the New York MTA and Nashville MTA on how agencies of vastly different sizes have already begun to feel the effects of more intense precipitation on this event. In New York, an intense storm in August 2007 overwhelmed pumps and drainage systems, which caused extensive damage to and forced the shutdown of most of the subway system. In Nashville, the flooding of the Cumberland River in May 2010 damaged a significant portion of the Nashville MTA's buses, paratransit fleet, and maintenance facilities, while also shutting down service for four days. In addition to these two examples, the report provides a "snapshot" of how several rural transit agencies were impacted during the 500-year flood of the Mississippi River in 2011. Flooding can impact transit agency assets and operations in several different ways. As mentioned in the example from New York, flash floods caused by intense rainstorms can overwhelm local

sewer systems, especially if they are combined sewer-stormwater systems, and prevent water from being pumped out of subway tunnels. Second, areas that are flooded may have bus service rerouted around them or temporarily suspended. Third, the flooding of rivers and streams can scour bridge supports, which damages bridges. Fourth, flooded rail tracks can cause signal circuit failure. Finally, the financial impacts from flooding can be substantial as was the case with one of Boston's subway lines that flooded in 1996, which was closed for several weeks and cost \$75 million to repair. Another event influenced by more intense precipitation is landslides in areas with steep hills and/or easily saturated soils. If severe enough, landslides have the potential to cut off transit service to large areas or at least force rerouting. Transit agencies near the Pacific coast (specifically Portland, San Francisco, and Los Angeles) and Honolulu have been affected the most by landslides in the past, while the New York MTA expects landslides in its service area to become more frequent in the future. A third event influenced by more intense precipitation is heavy snowfall. Heavy snowfall events usually result in significant disruptions to bus service, as the New York MTA reports that it can take up to 12 hours for normal bus service to resume after severe snowstorms despite the extensive use of snow-clearing equipment. It can also force agencies like the WMATA to only run their underground heavy rail service due to snow covering the third rail. Finally, drought is an event that is influenced by a combination of more intense but also less frequent rainfall. Droughts can cause water restrictions to be put in place, which can result in less frequent vehicle washing that negatively impacts the appearance of the vehicles. In addition, since hydroelectric power provides nearly half of the Pacific Northwest region's electricity needs, it is expected to be the most significantly impacted due to drought conditions. As a consequence, electricity rates will generally be higher, which results in higher energy costs for the region's transit agencies, especially those that utilize electrically powered rail vehicles and/or buses.

The second major climate impact discussed is the increase in the number of very hot days and/or heat waves. According to the climate studies investigated by the report, average temperatures in the United States are expected to increase between 4 to 11 degrees Fahrenheit by the end of the century depending on the emissions scenario. In addition, by the end of the century a 20-year heat wave is expected to occur every other year on average. These conditions can be further exacerbated by the “heat island” effect in urban areas, which can result in areas that are up to 5 degrees Fahrenheit hotter than surrounding suburban areas. These findings are of particular concern to transit agencies, since most are located within or provide service to densely developed urban areas.

Intense heat and heat waves cause several issues for transit agencies. First, very hot days can cause tracks to kink or buckle, which can damage the track, reduce vehicle speeds, and even cause derailments if the heat is particularly intense or prolonged. A recent heat wave in July 2010 that resulted in the WMATA, MBTA, Maryland Area Regional Commuter (MARC), and SEPTA reducing rail vehicles speeds and replacing damaged rails. Another example of this impact on operations is found in Portland Metro, which reduces rail vehicle speeds by 10 miles per hour on track areas with speeds over 35 miles per hour when temperatures exceed 90 degrees Fahrenheit. Second, electrical systems on trains, substations, and other areas can overheat and fail. This effect can be exacerbated by the system design, as is the case with Portland Metro’s substations, vending machines, and light rail vehicles. These systems were originally designed to operate in the mild climate the region had experienced in the past, but have begun to overheat as the number of days with temperatures exceeding 90 degrees Fahrenheit has increased. Third, overhead catenary wires can sag and lose tension, which can result in light rail vehicles losing electrical power. Fourth, in addition to their electrical systems, vehicles’ engines and air conditioning systems can overheat and fail, which reduces fleet availability and the level of comfort for customers within the vehicle, respectively. Fifth, customers and employees experience an increased threat of heat-related health issues, such as heat stress

and heat stroke that can lead to death if not treated quickly and properly. Intense heat also increases ground-level ozone, which can result in respiratory infections or lung inflammation. For vehicle operators, maintenance staff, and construction workers, these conditions can result in reduced activity and productivity for safety and health reasons. For customers, these conditions result in an uncomfortable environment at the stations and within the vehicle, while “choice riders” may avoid using transit altogether. Sixth, the potential for wildfires increases, with studies suggesting that an increase of almost 2 degrees Fahrenheit would result in a 200 to 400 percent increase in the median area burned by wildfires. These wildfires would primarily cause disruptions in transit service through bus rerouting or cancellation if no alternate route exists. Finally, increased electricity demands from air conditioning systems can result in regional blackouts. While some transit agencies have electrical redundancies, if the blackout is severe enough it can result in loss of power to rail vehicles, effectively halting service.

The third major climate impact discussed is sea level rise. The report found that a study by the IPCC estimated that sea levels would rise between 8 to 24 inches by the end of the century. However, more recent studies that account for additional factors such as accelerated ice sheet melting estimate a rise of 3 to 4 feet by the end of the century under high emissions scenarios. The report notes that sea level rise is not uniform in all areas due to different environmental factors such as plate tectonics, ocean circulation, and coastal dynamics. In addition, more than a third of the land in 180 coastal municipalities within the United States is below 6 meters (19.7 feet) in elevation. While many coastal urban areas have constructed artificial defenses such as levees and sea walls, many of these structures were not designed with future sea level rise in mind. Therefore, unless they are redesigned to accommodate for sea level rise, they will remain an ever-increasing threat for failure that would result in catastrophic damage to the areas they protect. The report presents the San Francisco Bay Area as an example of what impacts sea level rise could have on transit agencies in the future. The sea level in the Bay Area is

expected to rise 16 inches by mid-century and 55 inches by the end of the century. The 16-inch rise is roughly equivalent to a present-day 100-year flood for the region, which would result in significant damage to local infrastructure (roads, ports, rail lines, schools, etc.). A study by the local Metropolitan Transportation Commission found that areas of the Bay that had been filled in for development were most vulnerable to rising sea levels, which included both of the area's major airports and the transit lines that served them. Another example of a metropolitan area that is vulnerable to sea level rise is Miami, which has over 90 percent of its land below 6 meters above sea level. In addition, the estimated value of assets exposed to damage from a 100-year flood is currently above \$416 billion and expected to increase to over \$3.5 trillion by 2070.

The fourth major climate impact discussed is more intense tropical storms and hurricanes. Over the past few decades, the frequency and intensity of hurricanes in the Atlantic have increased due to an increase in sea surface temperatures of almost 2 degrees Fahrenheit. In the Pacific, the most intense hurricanes have become more intense even as the total number of storms has decreased. Overall, the climate models studied by the report indicate that these trends are expected to continue. Storm surges are one effect of tropical storms and hurricanes that are directly affected by the intensity of the storm as well as sea level rise. The report specifically references the US DOT's Gulf Coast Study as an example of how vulnerable the Gulf Coast area is to the effects of storm surges. In particular, 27 percent of major roads, 9 percent of rail lines, and 72 percent of ports are at or below 4 feet in elevation, and the report presents two figures showing the vulnerability of the Houston and New Orleans transit systems to storm surges. High winds are another effect of tropical storms and hurricanes that can cause disruptions to transit service in several ways depending on their intensity. First, they can cause trees to fall, blocking tracks, bus routes, or station entrances (and/or cause damage to assets). Second, felled trees can down power lines, cutting off power to electrified rail vehicles, substations, and communications equipment. Third, they can damage or destroy communications

antennas, disrupting or cutting off communications between vehicle operators, maintenance staff, and other employees from both each other and their supervisors. Finally, they can result in slow orders being issued for trains, as is the case with Portland's TriMet, which issues slow orders when wind speeds exceed 50 miles per hour. A third effect of storms and hurricanes is scouring and wave action on bridges. Bridge scour can compromise the foundation of the bridge piers and cause failure if left untreated. Severe wave action can destroy sections of bridges or entire bridges themselves, as was the case with the Highway 90 bridge in Mississippi.

In addition to investigating the science behind and potential effects of each of the four major climate impacts individually, the report mentions that the effects produced by each usually occur in combination with one another. The most notable example of this is the combination of sea level rise with a flood from intense precipitation or storm surge from a tropical storm or hurricane. The report provides examples of the potential damage caused by such a combination for both New York City and Boston subways. In addition, the report presents two national maps that display both the vulnerability of transit agencies to and the potential impacts from three of the climate change impacts discussed earlier: intense precipitation, sea level rise, and more intense heat.

The report briefly mentions that abrupt changes in climate could accelerate the rate at which the effects from each impact intensify and provides an excerpt from the USGCRP on the issue.

Next, the report summarizes how the identified climate stressors will impact various agency goals. The safety of customers and employees will become increasingly threatened by intense heat, which can cause personal health problems as well as cause trains to derail due to track buckling. In addition, flooding, storms, and high winds all present potential safety hazards. Achieving a state of good repair will become more difficult as assets deteriorate more rapidly from the effects of climate change. This could result in catastrophic asset failures for agencies that are already struggling to achieve a

state of good repair. Transit agencies will experience increased financial costs due to increased maintenance activities, accelerated asset replacement, and increased operating costs from more frequent extreme weather events. The mobility of the region may also be negatively affected due to increased transit service disruptions from extreme weather events and/or related asset failures. Increased disruptions can cause mode-shifts that overwhelm other types of infrastructure such as roads and highways. Finally, vulnerable and transit-dependent populations such as the elderly, disabled, and poor will be disproportionately affected by the deterioration of transit assets and disruptions in transit service caused by climate change.

The second section of the report concludes with a case study about the New York MTA and how it began to identify ways to adapt to the impacts from climate change. The MTA partnered with Columbia University in its Blue Ribbon Commission on Sustainability, which produced a 50-page report that provided local climate science related to transit in New York, analyzed the potential climate impacts on MTA's assets, identified the most vulnerable assets, and provided recommendations for both short and long term adaptation strategies. The report found that while the impact of only sea level rise on MTA assets was low, if sea level rise was combined with a storm surge the impact was extremely high. The report analyzed the potential damage that would be caused by a 100-year flood combined with a 4-foot rise in sea level. Such an event would flood most of Manhattan's subways and nearly all of the tunnels under the East River and those connected to the Bronx. The minimum recovery time from such an event to 90 percent of capacity was estimated between three to four weeks, though a full recovery could take one to two years based on responses from several engineers. The combined economic and physical losses from the event were estimated at \$84 billion. The report concluded with several recommended adaptation measures to address this vulnerability, which included installing flood gates, closing ventilation grates, and raising station and tunnel entrances. The MTA also actively participated in many state and local-level adaptation efforts for a

variety of different industries such as energy, public health, and agriculture. This involvement allowed the MTA to work more closely with climate experts, utilize climate scenarios consistent for other agencies, and bring the discussion of transit system impacts into the broader analysis of systems impacts.

2.3.6.3 Climate Risk Assessments

The third section of the report discusses how transit agencies can conduct their own climate risk assessment. The section begins by discussing the general framework followed by many previous assessments and provides links to several relevant guidebooks that were developed by state and local governments.

The first step in most risk assessments is to identify the current and future climate hazards that the transit agency faces. Climate data for such an analysis is usually downscaled from global models to a higher resolution for larger metropolitan areas. For areas and agencies that do not already have locally downscaled data, multi-state climate data is available from the USGCRP and FHWA's Regional Climate Effects Report, but only allows those agencies to identify more generalized impacts for their service areas. The report then provides a detailed list of the many different resources available to transit agencies for obtaining localized climate data.

The second step characterizes the risk of the climate change impacts identified in the first step on an agency's assets and operations. This is usually accomplished by comparing the likelihood of a climate change hazard occurring (such as sea level rise) with its potential magnitude of consequence (physical damages, service disruptions, etc.). It also important in this step to characterize the vulnerability of assets to the identified climate hazards based on their exposure, sensitivity, and ability to adapt.

The third step in the risk assessment process involves developing and assessing potential adaptation strategies. These strategies can include revising engineering standards for new assets, retrofitting existing assets, and modifying future system

planning. However, these strategies must be assessed based on their potential effectiveness, ability to address multiple climate hazards, and cost savings relative to implementation costs. In addition, agencies should seek to avoid over-designing their assets, which may yield unnecessarily high capital costs. The report provides a simple four-step process that could be used to design particularly critical infrastructure with adaptation in mind.

The fourth step integrates the adaptation strategies into all aspects and departments within the agency, which increases institutional awareness and involvement in addressing the issue. The report specifically recommends integrating adaptation strategies with asset management systems, planning processes, environmental reviews, and other systems.

The fifth step is to develop and implement an adaptation plan for the agency that specifies what groups and resources will be used as well as when specific strategies should be fully implemented.

As the agency carries out the adaptation plan, the final step in the assessment process is to monitor, reassess, and update the plan and its assumptions as improved climate data, new information on asset impacts and conditions, new adaptation measures, and changing demographic information become available.

The report continues by discussing the current state of the practice as it relates to risk assessments. In addition to the risk assessment developed by the New York MTA and Columbia University that was discussed in the previous section of the report, both the Los Angeles County MTA and New Jersey Transit were in the process of completing their own climate risk assessments. While the report recommends that transit agencies conduct a similar full risk assessment, budget constraints may limit agencies from doing so. While there is little information on transit-specific adaptation strategies, there are many strategies that have been developed by transportation-related entities that could provide guidance for transit agencies. These sources include experiences from other

transit agencies that are dealing with current weather events that other agencies may experience in the future from climate change, international agency design standards that have been modified for climate change adaptation, multi-modal adaptation strategies (specifically the USDOT *Gulf Coast Study*), and FHWA's pilot project on vulnerability assessments for state DOTs and MPOs. In addition, transit agencies should become more involved in local and state level climate adaptation efforts and follow best practices developed by such efforts. The report provides a table that details the climate adaptation actions taken thus far by transit agencies both within the US and abroad.

Next, the report discusses several elements key to successful adaptation efforts. First, adaptation efforts should be flexible to the uncertainties inherent in both climate change and the effectiveness of adaptation strategies. Agencies should modify their approaches as new information on climate change and feedback on the effectiveness of existing strategies becomes available. Second, adaptation assessments should include staff from across all transit agency departments, especially "frontline" staff. This allows staff to provide first hand information about issues within the system, which encourages engagement and buy-in to the adaptation process. Third, climate change adaptation strategies should be integrated into the agency's existing processes, not made into a separate system. Such integration increases institutional awareness of the effort, builds experience on the issue throughout the agency, and improves the effectiveness of the strategies being implemented. Fourth, the agency should seek to implement strategies that are cost effective even without climate change and/or strategies that achieve multiple goals at once. Fifth, agencies should plan and implement effective communication policies to provide information to customers through as many avenues as possible, including smart phones, websites, and mass media. Sixth, the agency should seek out external top-level officials that are supportive of adaptation efforts, as was the case with the mayor's offices of New York City and London. Seventh, a champion within the agency should be identified to be a central point of coordination for coordinating all

adaptation efforts, ensuring information sharing, and providing accountability. Eighth, interdisciplinary seminars should be developed to bring together staff from various departments to learn about and discuss the climate adaptation efforts the agency is undertaking. Finally, the agency should coordinate adaptation efforts with other infrastructure entities such as stormwater management agencies, state DOTs, and local environmental departments.

The third section of the report concludes with two case studies. The first case study discusses the second phase of USDOT's *Gulf Coast Study*, which conducted a risk assessment for the MPO region in Mobile, Alabama. The assessment sought to identify which transportation assets were most critical for the region, their vulnerability to extreme weather events and climate change, and how they could be protected or adapted for various climate change impacts. The report's case study focuses primarily on the aspects of the assessment that related to transit, specifically Mobile's Wave Transit agency. The criticality of transportation assets were analyzed qualitatively based on three factors: operational, socioeconomic, and health and safety. Socioeconomic factors included the level of transit service provided to transit-dependent and environmental justice populations and accessibility to major employment centers and attractions. By overlaying the region's fixed-route bus service with major employment centers and attractions, the study found that the Mobile transit networks provides service to many of the area's vulnerable and transit-dependent populations. Operational factors in the assessment included the types and variety of transit services available to the region. Health and safety factors included the ability for the transit agency to provide access to medical and other safety facilities and evacuate people during emergencies. Due to its location near the coast, Wave Transit provides evacuation services in the event of hurricanes under the direction of the Mobile County Emergency Management Agency. The study found that both of Wave Transit's fleet facilities, as well as its fixed route and demand-responsive fleets were critical transportation assets for the region. The second

case study discusses the Los Angeles County MTA's (Metro) efforts behind developing its own risk assessment. The agency used the *Guidelines for Transit Climate Action Planning* developed by the American Public Transportation Association (APTA) Climate Change Standards Working group as a starting point for its action planning process, which included both adaptation and mitigation. In conducting its assessment, the Metro investigated the current practices at other U.S. transit agencies, formed a technical advisory committee, and hired a consultant with experience in climate change adaptation. For Los Angeles, the main climate change impacts that will affect transit are more frequent and intense heat waves, more frequent intense precipitation, more frequent wildfires, and sea level rise. Initial adaptation strategies to address these impacts include designing increased flexibility into the transit system, decentralizing asset storage, and identifying flood prone areas. The agency has also sought to integrate climate change adaptation into its practices by adopting an agency-wide environmental policy in 2009, including climate change adaptation measures in an update to its design criteria, and using its Environmental Management System as a climate change management tool.

2.3.6.4 Strategies

The fourth section of the report presents a variety of strategies that transit agencies could use to adapt to climate change impacts. The report first discusses the four different broad categories of climate adaptation strategies. The first category consists of strategies to absorb increased maintenance and repair costs while improving response times when incidents occur. The second category consists of strategies that retrofit and strengthen existing assets and infrastructure while also incorporating updated design standards for new assets and infrastructure to increase their built-in resiliency to climate change impacts. The third category consists of strategies to increase the redundancy of transit service so that service interruptions in one mode can be mitigated by available service on others. The fourth category consists of strategies that involve moving

infrastructure and assets away from extremely vulnerable areas if feasible, and abandoning them if not. The various adaptation strategies presented in the report are not intended to be comprehensive, but instead should be seen as ideas for agencies to shape and implement individually based on their local characteristics. The strategies discussed in the report are not categorized in the four categories defined previously, but are instead categorized by the climate impact they address. In addition, the report provides many examples of how transit agencies both in the United States and around the world have implemented such strategies.

The first set of strategies address ways that transit agencies can adapt to flooding caused by intense precipitation, sea-level rise, or storm surge. First, agencies should try to relocate assets and facilities away from low-lying or flood-prone areas. The report presents a notable example in Honolulu's transit agency, which relocates its bus fleet to the storm shelters they provide emergency service to during flood conditions. Second, pumps located in subway tunnels and stations should be properly rated for handling various flooding conditions. The report provides several examples of how pump design standards vary greatly between agencies due to wide variations in local experience, conditions, and regulations. Third, ventilation grates should be modified to prevent street-level runoff from entering subway tunnels and stations. Notably, after the flooding caused by storms in August of 2007, the New York MTA held a design contest for new, raised ventilation grates that also served as street furniture. Fourth, agencies could construct physical barriers to prevent water from entering the system and/or improve the capacity of drainage systems for the water that does. The report presents examples from New York City, Toronto, Tokyo, and Southeast Asia on how transit agencies implemented different levels of physical protection and drainage ability into their systems depending on the location and criticality of the vulnerable infrastructure. Fifth, bridge design standards could be modified to provide greater protection to bridge piers to prevent scour. In addition, agencies should include the risk of higher river flood levels from climate

change in the bridge design process, as was the case with TriMet's Portland-Milwaukie line bridge. Sixth, agencies could reduce the runoff produced by park and ride lots, administrative buildings, maintenance facilities, and storage yards by implementing green infrastructure practices such as rain gardens, stormwater ponds, pervious pavement, and natural vegetation buffers. Such practices not only prevent or reduce localized flooding, but also allow water runoff to be absorbed and treated by natural processes. An example of such practices is presented in Kansas City's new Bus Rapid Transit (BRT) system that has 30 stations with rain gardens in bump-outs and a pervious concrete parking lot. Other green infrastructure practices include the use of vegetated "green roofs" and rain barrels or cisterns for capturing excess runoff from roofs. Examples of these practices include the New York MTA's Leadership in Energy and Environmental Design (LEED)-certified Corona maintenance facility, the USDOT's headquarters building, and San Francisco MTA's headquarters building. Seventh, agencies could seek to integrate with local and state level adaptation efforts to further increase the effectiveness of other adaptation strategies. An example of such a strategy is Transport for London's involvement with the Greater London Authority's "Drain London Programme." Finally, agencies could encourage more transit-oriented development (TOD) around their stops and stations in order to preserve natural systems that can prevent or reduce the impact of flooding. Examples of such adaptation-focused TOD efforts are the Houston-Galveston MPO region and the City and County of San Francisco.

The second set of strategies address ways that transit agencies can adapt to landslides caused by intense precipitation. Agencies could implement better stormwater management systems to divert water away from steep slopes to prevent the soil from becoming saturated. Additional hardening in areas that are vulnerable to landslides is another option, as was the case with the Hawaii State DOT.

The last set of strategies discussed in the report address ways that agencies can adapt to the effects of more intense heat and more frequent heat waves. First, the rail-

neutral temperature of the rail could be increased to allow for more expansion during high temperature days to prevent buckling. However, an agency should adjust this increase based on local operating and environmental conditions, since setting the rail-neutral temperature too high could result in rails breaking during colder conditions. Other ways to reduce the possibility of buckling include implementing more direct monitoring systems for rail temperature, installing expansion joints, and reinforcing or upgrading the rail foundation. The report provides examples of how Amtrak, the United Kingdom, and Portland's TriMet have implemented such strategies. Second electrical components could be better ventilated or cooled in order to prevent electrical failure. Finally, the agency could take steps to protect the safety of both their workers and patrons. Such steps could include developing and implementing a heat action plan, installing energy-efficient air conditioning on revenue vehicles, using heat-resistant construction materials and reflective paint, and providing shade in the form of shelters or landscaping for patrons near transit stops. Examples of implementation of these measures include TriMet's installation of improved electrical cooling systems on its new buses that utilize computer monitoring and idle-off technology to increase fuel economy, New York MTA's application of light-colored or white paints and membranes to its new Corona maintenance facility, and the Transit Services Division of the Tucson Department of Transportation's station designs for their new streetcar system as well as efforts to improve shading at or near its bus stops through a combination of landscaping, stop relocations, and new shelter design.

2.3.6.5 Implementation

The fifth section of the report discusses ways that transit agencies can implement climate adaptation strategies through several existing processes that either the agency conducts on its own or is participatory in. Implementing climate adaptation strategies through existing processes is important because the effects of climate change will impact

all agency departments. In addition, implementing the strategies through existing processes and agency-wide increases institutional awareness of the need for climate change adaptation, thereby increasing the effectiveness of the strategies being implemented.

The first existing area that climate adaptation strategies should be implemented through is organizational culture and budget priorities. While issues such as short-term performance goals and limited funding sources have resulted in many agencies pushing the issue of climate change to the side, it is only a matter of time until the issue will cause significant damage to agency systems if left unchecked. The report encourages agencies to utilize responsible risk management practices in order to protect and preserve the system from future damage and notes that a Federal Emergency Management Agency (FEMA)-commissioned study estimated that every dollar spent on hazard mitigation results in approximately four dollars of avoided damage costs. The Washington Department of Transportation is presented as an example of how agencies can incorporate climate adaptation into the scope of their existing responsibilities in a cost-effective manner.

The second process that adaptation strategies can be incorporated into is asset management systems. Asset management systems allow agencies to inventory their assets, evaluate their risk, and prioritize their rehabilitation and replacement. The report mentions the FTA's initiative to encourage transit agencies to develop and/or improve their asset management practices through pilot projects and research on best practices. In discussing ways in which climate adaptation can be linked to asset management, the report specifically references the "Transportation Asset Management Systems and Climate Change Adaptive Systems Management Approach" report by Meyer, Amekudzi and O'Har (2009) and presents a table that shows how climate change can be linked to the components of asset management. One example of such a link is incorporating climate change considerations into the activities described in both short and long-range

plans and design guidelines. The report presents a case study on how Transport for London incorporated climate adaptation into its asset management system. The incorporation came about as a result of the United Kingdom's Climate Change Act of 2008 that required all government agencies to report on their climate adaptation efforts. Once the UK government provided a set of climate projections for agencies to use, by the end of 2010 all of the services under Transport for London had assessed and updated the risks to their assets and operations from climate change, which were incorporated to TfL's risk management system. TfL measures risk based on probability of occurrence and the potential impact to both the organization itself and its stakeholders (e.g. patrons). It uses a multi-step process to identify each potential climate impact, quantify its probability of occurrence, quantify the consequences of its occurrence, and assess a risk score for prioritization purposes. While the agency is able to easily estimate the costs for potential adaptation measures and their avoided damages, it is less able to estimate the potential economic, political, and reputational costs resulting from disrupted transit service. Examples of adaptation measures that TfL has implemented include installing air conditioning on new trains and increasing ventilation in tunnels to reduce temperatures in trains and on station platforms, requiring new buses have white roofs, tinted windows that open, upper ventilation, and air condition in the driver's cabs, identifying and installing preventive measures in flood-prone areas, and incorporating flood adaptation measures into new capital projects like Crossrail.

The third process that adaptation strategies can be incorporated into is metropolitan and statewide transportation planning. Transit agencies should actively participate in the planning process, because it is through the planning process that capital investments in transportation are prioritized, locations for new infrastructure are determined, and network disruptions are analyzed. The report discusses how these and several other activities within the planning process can be used as opportunities to incorporate climate adaptation. While such incorporation activities are not widespread in

the transportation industry, the report highlights several notable examples from Connecticut, San Francisco, New Jersey, Oahu, Portland, and New York. In addition, because of the lack of federal regulatory requirements for state DOTs and MPOs to consider climate change in their transportation plans, agencies primarily rely on direction from state-level entities.

The fourth process that adaptation strategies can be incorporated into is Environmental Management Systems (EMS). An EMS is an organizational plan for reducing environmental impacts. Because an EMS is normally used to change an agency over time, respond to emergencies, and provide performance evaluations across the entire agency, it can be useful in applying such functions to address climate adaptation. The most notable example of the use of an EMS for such a purpose is presented in the Los Angeles Metro.

The fifth process that adaptation strategies can be incorporated into is environmental review and project management. The report notes that, at the federal level, the White House Council on Environmental Quality has issued draft guidance that would require consideration for climate change adaptation and mitigation in environmental documents covered under the National Environmental Policy Act (NEPA). At the state level, the report finds two examples of policies that require climate change consideration during the environmental review process. The first example is the modification to the California Environmental Quality Act (CEQA) as a result of an executive order by the governor that directs public agencies to consider the potential impacts to the environment for developments that are located in areas vulnerable to the impacts of climate change. The second example was the Washington State DOT's adoption of a policy that requires climate change consideration in all environmental impact statements performed under the state's Environmental Policy Act. The policy explicitly and clearly articulates the actions WSDOT staff should take to consider climate change and expresses to them the need for taking action on climate change.

The sixth process that adaptation strategies can be incorporated into is floodplain assessment. This activity is most important when determining the location for new transit facilities. Current practice dictates that if a proposed transit facility that is receiving federal funding is located within the 100-year floodplain as determined by FEMA's flood maps, then the environmental impact statement must include an analysis of the potential risks and flooding impacts to the facility. In addition, if the preferred alternative still lies within the floodplain, the Environmental Impact Statement (EIS) must include the FTA's finding that it is the only practical alternative and information supporting alternatives to avoid or reduce impacts to the floodplain. Existing facilities are assumed to have no impact on the floodplain and, if protected by a flood wall, are also assumed to not impact a flood zone or be impacted by flooding. The heavy reliance on flood maps for environmental impact statements makes it important that the maps are updated regularly and with accurate data. Newer maps should also incorporate projected changes to the floodplain over time using either a more extreme flood condition (such as a 500-year flood) or expert elicitation.

The seventh process that adaptation strategies can be incorporated into is real estate acquisition and relinquishment of assets. New transit facilities should be located in areas that are less prone to the effects of climate change and can be adapted in the future if necessary. In addition, the cost-effectiveness of proposed adaptation measures to existing facilities should be compared to relocating a facility to a more protected and adaptable location.

The eighth process that adaptation strategies can be incorporated into is design and construction. While past designs have incorporated historical weather patterns, new designs should consider how weather patterns would change over the life of the asset. An example of such action is New Zealand's transportation department, which incorporated climate change considerations into its bridge design standards. The report notes that while the process of developing new design standards can be time-consuming and

exhausting, the lack of industry-wide design standards should make this process easier for the transit industry. The four main design areas that should be modified because of their sensitivity to the effects of climate change are subsurface conditions, material specifications, cross sections and standard dimensions, and drainage and erosion.

The ninth process that adaptation strategies can be incorporated into is the retrofitting of assets. Agencies should identify and retrofit existing assets that are most vulnerable to climate hazards as well as utilizing regular maintenance and rehabilitation activities to perform retrofits on other assets.

The tenth process that adaptation strategies can be incorporated into is maintenance. Since the effects of climate change are expected to put additional stress on facilities and assets, maintenance activities should be increased to avoid damage.

The eleventh process that adaptation strategies can be incorporated into is emergency preparedness, response, and recovery. Specifically, the Standard Operating Procedures (SOPs) that agencies utilize before, during, and after extreme weather events will become more important as climate change progresses. The report presents the London Underground's use of SOPs to identify areas of responsibility for employees, thresholds for enactment, and vulnerable infrastructure that may be affected. In addition, the report draws from two FTA reports on best practices for hazard and disaster preparedness, response and recovery (*Disaster Response and Recovery Resource for Transit Agencies* and *An Introduction to All-Hazards Preparedness for Transit Agencies*) to identify areas for improvement. First, emergency management plans should explicitly define staff responsibilities, plans of action, and standard operating procedures for a range of emergency scenarios. Second, the emergency plan should describe procedures and strategies for protecting and/or operating bus and rail fleet vehicles during extreme weather events. These include actions such as moving buses out of flood prone areas, parking buses inside structurally sound buildings, fueling vehicles prior to predicted emergency events, and splitting a fleet of vehicles between two or more locations to

increase the survivability of the entire fleet. Third, transit facilities should be designed to survive and operate during emergency situations. Fourth, back-up power supplies such as batteries for radios, recharging abilities through vehicles, and back-up generators at facilities should be available so that the agency can continue to operate when primary power is lost. Fifth, important agency documents that are in electronic format should also be made in hard copy in case of power failures. Sixth, the job responsibilities of key employees during emergencies should be included in the job description if the responsibility is mandatory, otherwise voluntary commitments should be obtained prior to an emergency event if possible. Seventh, transit agencies should coordinate their emergency efforts with state and local emergency planners. Eighth, mutual aid agreements between transit agencies could be formed so that vehicles and equipment can be made available in case of an emergency at one agency. Finally, insurance coverage should be acquired by the agency that can meet its needs after extreme weather events. Transit can also play an important role in the evacuation of transit-dependent populations to sheltered areas in the event of hurricanes, heat waves, storms, and wildfires that are expected to become more frequent in the future. Best practices for evacuating such populations include establishing evacuation routes and stops in advance so that passengers are aware of what services are available to them before the event occurs, coordinating with local school bus and private transportation providers to pool resources, establishing a coordinator of service delivery within an Emergency Operations Center, and establishing a point of contact at each emergency shelter to identify transportation needs. In addition, to protect the safety of its operators and passengers, the agency should establish thresholds above which operations are ceased. The report provides some statistics on how important transit's role is in evacuating transit-dependent populations from a survey conducted after Hurricane Katrina. Unfortunately, a study conducted by the FTA found that few transit agencies specifically plan for the evacuation of the transit-dependent populations they serve. The report recommends several practices that agencies

should adopt to address this issue. These include practices such as establishing pick-up locations for transportation to shelters before an evacuation occurs; developing procedures to coordinate evacuation of transit-dependent populations with other emergency planners and first responders, conducting evacuation exercises with operators, first responders, and transit-dependent populations to gain experience, and identifying populations that have limited English proficiency, disabled persons, and elderly adults. Finally, in recovering from an emergency, agencies need the ability to quickly allocate and spend funds for retrofitting, rebuilding, or replacing damaged assets so that service can be restored. Transit agencies should work with their MPOs and state agencies to ensure that procedures are in place to provide access to emergency funds and expedited review for spending requests.

The final process that adaptation strategies can be incorporated into is performance measures. While it is important that the agency monitor its performance with regards to implementing climate adaptation strategies, it is more important to measure how those strategies are making progress towards the larger end goal of making assets and facilities more resilient against the effects of climate change. A good measure of such progress is asset conditions, which should be better maintained under climate adaptation strategies.

2.3.6.6 Conclusion

The final section of the report briefly discusses several conclusions that can be drawn from the report's findings and recommendations. First, transit agencies are responsible for managing the risks to their assets and operations, which requires improving their resiliency to the effects of climate change through adaptation and mitigation. Such improvements will help agencies achieve and maintain a state of good repair and also increase their ability to provide service during weather emergencies. Second, few agencies both domestically and abroad have begun to address the issue of

climate change adaptation. In addition, little research has been conducted on what specific impacts climate change will have on transit assets and operations and few solutions on how transit systems can adapt. Third, despite a lack of transit-specific climate adaptation research, transit agencies can increase their participation in ongoing climate change efforts at the state and local level to gain more experience and knowledge about how climate change will impact their service area specifically and what options are available to adapt to those impacts. Finally, climate adaptation strategies must be implemented through existing agency processes to increase their buy-in and ultimately their effectiveness.

2.3.7 Climate Adaptation at the New York MTA

As with the State of Good Repair Initiative, there was one transit agency that had already conducted its own climate change adaptation assessment before the issue of climate change adaptation in the transit industry was taken up as an initiative at the national level. The New York MTA formed a commission in 2007 that was tasked with developing a series of recommendations for making the agency more sustainable [14]. The final report published by the commission in 2009 included a section that provided several recommended actions the agency should take to begin to adapt its assets and operations to the effects of climate change.

2.3.8 Greening Mass Transit & Metro Regions

This report was developed by the Blue Ribbon Commission on Sustainability and the MTA, which was appointed in 2007 by the Executive Director of the MTA. The purpose of the Commission was to develop sustainability strategy recommendations for the MTA and its constituent agencies. The Commission was divided into several working groups that covered different topics related to sustainability such as energy, water management, and climate adaptation. Each task force developed its own report that

presented its findings on the topic and provided several types of sustainability recommendations for the MTA to consider: transformational, near-term, and legislative. These task force reports were combined and summarized to produce the final report. While this report discusses many different types of sustainability strategies that have ties to climate change, this review is most interested in the findings and recommendations of the climate adaptation task force. These findings and recommendations were primarily drawn from the task force's own more detailed report entitled *MTA Adaptations to Climate Change – A Categorical Imperative*.

2.3.8.1 Climate Adaptation

While most of the report is devoted to developing strategies the MTA can implement to mitigate its impact on climate change, this section of the report notes that the agency must also develop strategies to adapt to the impacts of climate change that are already occurring and are expected to intensify in the near future. A team of climate science and economics experts identified three climate trends that would have the most significant impact on the MTA's assets and operations: higher average temperatures, rising sea levels and related storm surges, and increased storm activity with more intense precipitation and resulting flooding. Increasing average temperatures will increase demands on vehicle and facility cooling systems that results in higher energy demands for the system, which in turn places additional stress on the local energy grid. Sea level rise (SLR) and storm surges as well as more intense precipitation can cause flooding that results in more significant impacts. SLR will increase areas where flooding could occur regardless of storm size, which puts many MTA assets at greater risk for flooding, such as subway tunnels and stations. The increased risk of storm surge flooding also affects emergency planning, facility design, protection of rolling stock, and insurance programs. Adaptation strategies include inspection of existing or planned facilities within the expanded flood areas, utilization of outside insurance programs, increased pumping

capacity in subway tunnels and stations, raised subway and tunnel entrances, sealing ventilation grates in high-risk sections of the subway, and the construction of strategic storm barriers. Besides subway tunnels and stations, the report identifies several other locations that are vulnerable to flooding, including Metro-North's Hudson and New Haven Lines, Hunters Point Station, and the Long Island Rail Road East River tunnels.

2.3.8.2 Current Efforts

The climate adaptation task force found that adaptation strategies such as storm protections and facility redesigns were already taking place in an ad hoc manner at several MTA agencies. While the MTA had yet to develop a unified adaptation plan to coordinate such activities, the report found that the MTA's existing storm policies would be a useful starting point for implementing adaptation strategies to address SLR, storm surge, and increased precipitation. The MTA was also participating in three climate-related task forces: the New York State Sea Level Rise Task Force, the ClimAID Project Task Force, and the New York City Climate Change Adaptation Task Force. Finally, the MTA had recently completed a review of its storm vulnerabilities and related policies after the storm events of August 2007 that caused significant disruption to the system. The review resulted in the implementation of over two dozen projects in the areas of operations, engineering, and communications. Operational improvements included the creation of the MTA Emergency Response Center, establishment of early warning and response capabilities, and a revision of the storm operating protocol. Engineering improvements primarily involved corrective engineering and procedural measures for the most flood-prone areas. Communication improvements included installing wireless communication capabilities to allow cell phone service in subway tunnels and equipping personnel at Long Island Railroad, Metro-North Railroad, and Bridges and Tunnels with additional communications devices.

2.3.8.3 Recommendations

The final portion of the climate adaptation section of the report offers several recommended actions that the MTA should undertake based on the findings of the climate adaptation task force. The only transformational recommendation the report makes is for the MTA to develop and implement a climate adaptation decision-making matrix to identify the best strategies for adapting existing assets based on a comparison of their risk/vulnerability to the effects of climate change to their value to the system.

The report also offers ten near-term recommendations that the MTA should consider. First, the MTA should establish a climate adaptation policy position that explains the necessity for such action, the MTA's commitment to developing an adaptation master plan, coordinating adaptation efforts with other infrastructure agencies, and taking a leading role in being an example of how transit systems can adapt to climate change, and recognizing that a balance of mitigation and adaptation is needed to properly address the effects of climate change. Second, the MTA should develop a climate change database that should contain climate data and projections based on the latest information and scientific methods available for the entire MTA service area. The database should be readily accessible by MTA staff and be updated regularly. Third, the MTA should conduct a vulnerability and risk assessment of the assets, facilities, operations, income streams, and insurance programs of the MTA's constituent agencies. The assessment should be scenario-based and assess the vulnerability of the current asset inventory based on current climate data as well as future inventory and climate projections in the 2020s and 2050s. Fourth, the MTA should develop a climate change adaptation master plan based on the results of the second and third recommendations with adaptation strategies projected out at least 100 years. This time horizon will allow the MTA to consider the long-term impacts of climate change on existing major capital assets and if decisions on future capital projects need to be reevaluated. Fifth, the MTA should establish a Pre-Disaster Plan for Post-Disaster Redevelopment in coordination with local, state, and federal governments along with input from local stakeholders. Such a plan will better

prepare MTA agencies for recovering and learning lessons from emergency weather events. Sixth, the MTA should form an Adaptation Priority Task Force (APT) that will be responsible for identifying ways to incorporate climate adaptation strategies into ongoing agency projects or practices. Seventh, the MTA should form an internal Adaptation Team (AT) to represent the agency's interest in outside climate change efforts while also partnering with professional organizations and academia to provide educational resources to MTA constituent agencies on climate science and climate adaptation. Eighth, the MTA should develop and utilize a cross-impact checklist for its adaptation and mitigation projects. A completed checklist for each project will allow the agency to determine if the proposed project needs to be modified so that the cross-impacts can be at best minimized or at least balanced if the outcomes are mutually incompatible. Ninth, the MTA should establish a Climate Adaptation Resiliency Evaluation (CARE) procedure that will be activated when a proposed project is located in a current or future flood zone. Finally, the MTA should take a strong leadership role on climate change issues at the local, state, federal, and global levels and be an advocate for climate adaptation and mitigation policies.

The climate adaptation section of the report concludes by briefly discussing the three primary effects of climate change that will pose the greatest risks to the system and the report's recommendations for adapting to them.

2.3.9 Climate Adaptation Outside the Transit Industry

Climate adaptation is an issue that concerns other fields outside of the transit industry, including local, regional, and state governments. A guide was developed in 2007 by King County and the University of Washington to help any local, regional, or state government begin to prepare for the effects of climate change [15].

2.3.10 Preparing for Climate Change – A Guidebook for Local, Regional, and State Governments

This document was developed jointly by The Climate Impacts Group at the University of Washington and King County, Washington as a guide for decision-makers at local, regional, and state governments on how to prepare for the impacts from climate change. The guide begins with an introduction from King County Executive Ron Sims, who discusses the incredibly positive turnout at a recent conference on climate change that was hosted in Seattle and the need to evaluate both adaptation and mitigation strategies in addressing climate change. He also calls on local governments to take action on what has already become the challenge of an entire generation.

2.3.10.1 Background on Climate Change

The second chapter of the guide seeks to educate decision-makers about climate change and its impacts. It begins by providing a general explanation of the “greenhouse effect” and how increased fossil fuel use, deforestation, and agricultural activities have intensified this effect by increasing the concentration of greenhouse gases in the atmosphere. The guide provides several tables and figures showing the data behind this change. The second chapter concludes by discussing the projected impacts of climate change at both the global and regional level. Specifically, the guide analyzes the results of a national U.S. assessment conducted in 2000 and presents a figure from the assessment that outlines how climate change is projected to affect different regions of the country.

2.3.10.2 Why Governments Should Prepare

The third chapter of the guide outlines the case for governments to prepare for climate change. It begins by discussing several reasons why governments cannot afford to wait to prepare for climate change. These reasons include the reality that climate

change is already occurring; while significant reductions in greenhouse gases are possible, they are unlikely to be stabilized or reversed in the short term; climate change is expected to occur even after greenhouse gases have stabilized; climate change will likely lead to irreversible losses in certain areas; and climate change will have largely negative economic consequences, but could also create economic opportunities.

Next, the guide outlines several reasons why governments should not just act on climate change now, but be proactive in their approach. These reasons include the idea that planning for future events can benefit those in the present; preparing for climate change is part of “good government”; areas that are expected to be impacted the most have a responsibility to be the most proactive; proactive actions are more effective and less costly than reactive actions when climate impacts occur; thinking strategically can reduce the future risk of the system while increasing future benefits; and anticipating changes can add present value to current investments. Finally, the third chapter presents several common challenges governments face in preparing for climate change and provides a response for addressing each. These include challenges such as a lack of information on how climate change will specifically impact a local area, the belief that actions on climate change should be handled at higher levels of government, the strategy that climate change can be addressed when the effects can be “seen”, a community that wants to only focus on mitigation strategies for addressing climate change, waiting to see if other communities begin planning for climate change, and a lack of time, money, or political resources to act.

The remaining chapters in the guide are primarily devoted to discussing the five milestones that help governments prepare for climate change.

2.3.10.3 Initiate a Climate Resiliency Effort

The first milestone is to initiate a climate resiliency effort. The fourth chapter of the guide discusses the first part of initiating a climate resiliency effort, which is how

governments can identify the climate change impacts that will affect their systems. This involves collecting and reviewing climate information (which includes identifying sources of information, determining what data to collect, and understanding the certainty of the data) and, based on the climate data findings and other factors such as the community's interest and degree of support, determining the government's level of commitment to preparing for climate change.

The fifth chapter discusses how governments can build and maintain support for climate change efforts. This involves identifying (or cultivating) a preparedness "champion" within the organization, identifying and understanding the target audience for outreach efforts, developing a clear and explicit preparedness message, and spreading the preparedness message both internally and externally.

The sixth chapter explains how to build a climate change preparedness team. It discusses reasons for forming such a team, how to select team members and their leader, what the team should do, and, if limited resources make forming a team unfeasible, how to assign a point person for climate change preparedness.

The seventh chapter discusses the final step in initiating a climate resiliency effort, which involves identifying planning areas and evaluating the current and expected climate stresses on them.

2.3.10.4 Conduct a Climate Resiliency Study

The second milestone is to conduct a climate resiliency study, which is a two-step process. The first step, discussed in the eighth chapter, is to conduct a climate change vulnerability assessment for the planning areas identified previously. Specifically, this process includes reviewing and supplementing the climate information collected during the first milestone, conducting a climate sensitivity analysis, evaluating the adaptive capacity of systems within planning areas, and finally analyzing the results of the study. The results of the vulnerability assessment are then used to conduct a climate change risk

assessment, which is discussed in chapter nine. This involves estimating the risk to each planning area based on the product of the consequence of an impact occurring and its probability or likelihood of actually occurring. The results of the risk and vulnerability assessments are combined to identify priority planning areas that are both important to the community and/or government and also vulnerable to the effects of climate change.

2.3.10.5 Set Goals and Develop a Plan

The third milestone is to set preparedness goals and develop a preparedness plan. The tenth chapter of the guide discusses how to establish a vision for a climate resilient community, set preparedness goals based on that vision, identify potential preparedness actions to take, and finally select and prioritize the actions. The vision, goals, and prioritized list of preparedness actions become part of the preparedness plan.

2.3.10.6 Implement the Plan

The fourth milestone is to implement the preparedness plan. The eleventh chapter discusses two primary ways to ensure that the plan is implemented successfully. First, the correct implementation tools should be in place based on the individual characteristics of the government and the community that it serves. Second, governments should manage the uncertainty and risk associated with the plan, which could include implementing “no regrets” actions in the early stages of the plan and/or utilizing quantitative modeling for more accurate climate projections.

2.3.10.7 Monitor and Update

The fifth milestone is to measure progress and update the preparedness plan, which is discussed in the twelfth chapter of the guide. The guide specifically discusses how governments can develop their own “measures of resilience” for measuring progress, review their initial assumptions, update their preparedness plans based on more specific or urgent climate information, and share their learning with other entities.

CHAPTER 3

METHODOLOGY

This chapter discusses the methodology that was used to conduct a case study of how MARTA can address climate change adaptation through its asset management program. This includes discussions on the climate modeling process used to identify the most significant climate trends for MARTA's service area, what interviews were conducted with MARTA staff, and how the information gained from the interviews was used to both visualize locations that were vulnerable to the identified climate impacts and develop potential climate adaptation strategies.

3.1 Climate Modeling Approaches

In general, climate models that project future climate conditions are beneficial to the development and implementation of effective adaptation strategies. This case study utilized two climate-modeling approaches to identify the most significant climate stressors in the MARTA service area.

3.1.1 Initial Modeling Approach

The material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

Dr. Aris Georgakakos and the Georgia Tech Water Resources Institute (GWRI) represent some of the best research capabilities in the United States with respect to analyzing changing climate variables. Given their location in Atlanta, they have special expertise on the climatological conditions in Georgia and in particular in the northern Georgia region. Dr. Georgakakos approaches climate change and its impacts primarily from the perspective of hydrological phenomena, thus he is not only interested in the actual weather-related event, e.g., the amount of precipitation that falls, but also with

what happens to the precipitation once it reaches the ground and makes its way to rivers and streams or enters the groundwater.

Figure 3 shows the grid system that was used in the modeling exercise for the Atlanta region that corresponds to the MARTA service district. Twenty-three cells (12 km by 12 km) were identified from the model as being most relevant for the analysis, selected to cover the MARTA service area. Longitude/latitude data were provided for each cell. The climate variables estimated included precipitation, average temperature, maximum temperature, and minimum temperature (the temperature was measured in Celsius and the precipitation in millimeters/day). There was no capability to estimate the number of extreme weather events. Historical data from 1972 to 2010 for every day in each of the 23 cells was obtained and analyzed. The historic data indicate that in general average temperature, maximum temperature and the number of days over 95 degrees Fahrenheit have increased over this 29-year period. Precipitation levels are less certain, with a serious drought over the past several years in northern Georgia skewing precipitation trends toward no net change over prior decades where trends tended to be toward higher precipitation levels.

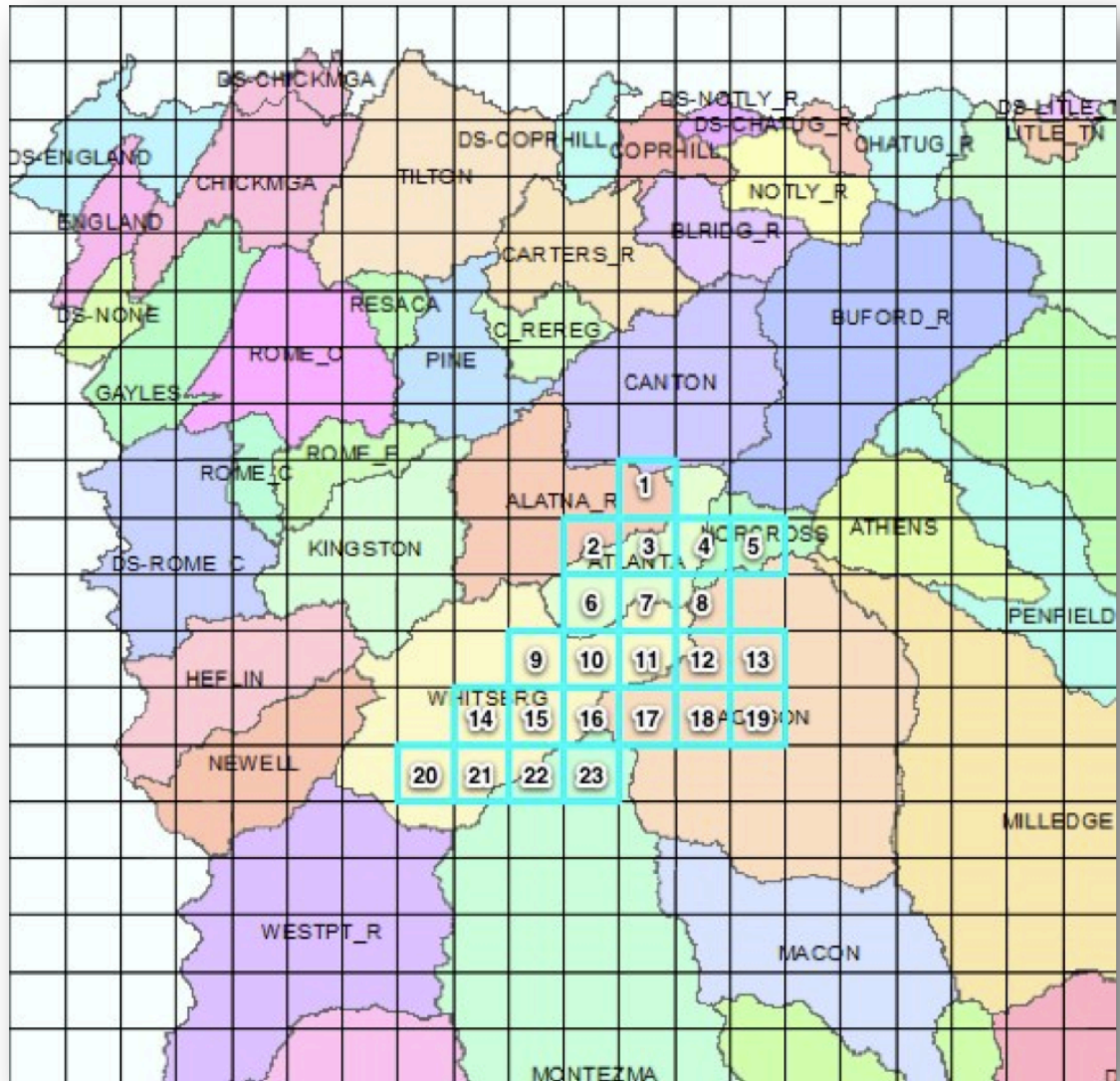


Figure 3: Grid System Used for Climate Variable Forecasting, MARTA Region

Not surprisingly, and an indication of the difficulty in forecasting site-specific climate variable changes, the percent change in each of the 23 cells for each variable for a specified time period differs; in other words, precipitation levels vary across the region. Thus, for example, precipitation change in cell 23 is different than that in cell 1 in a given time period, reflecting local meteorological conditions.

For the 23 cells, the GWRI provided data on average annual maximum temperatures, average annual minimum temperatures and average annual precipitation

values from 1972 through 2100. Daily values for the three different types of data were averaged to determine average annual values. For example, the maximum daily temperatures for the different cells were collected beginning from 1/1/1972 through 12/31/2010. Seven Global Climate Models (GCMs) were used in estimating the maximum daily temperatures through 12/31/2100: CGCM3.1 (Canada); CM3 (France); CM2 (USA); CM4 (France); Medres (Japan); ECHO (Germany/Korea) and ECHAM5 (Germany). These seven GCMs were used to generate values only under the A1FI emissions scenario, which is the highest emissions scenario within the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES). The maximum daily temperatures were then averaged to estimate the annual average maximum temperature for each year.

3.1.2 A Supplementary Modeling Approach

While the initial modeling approach conducted by the GWRI allows for easy identification of significant climate stressors under the highest emissions scenario, it is more practical to consider multiple plausible future scenarios when developing a climate adaptation plan for a transit agency. John Patrick O'Har's more comprehensive climate modeling approach for the Atlanta region was utilized to supplement the results of GWRI's initial approach. More detail on the climate models, climate data, and downscaling processes behind this approach can be found in O'Har's forthcoming dissertation *Transportation Asset Management and Climate Change: An Adaptive Risk-oriented Approach* [17].

In his modeling approach for the Atlanta region, O'Har utilized climate data from the United States Geological Survey's (USGS) online Geo Data Portal (GDP) (<http://cida.usgs.gov/climate/gdp>). The GDP provides downscaled temperature and precipitation projection data utilizing the latest, state-of-the-art climate projections to a resolution of 7.5 square mile (12 square kilometer) grid squares. This climate projection

data was collected for three different SRES emissions scenarios: A1FI (high), A2 (mid), and B1 (low). Within these emissions scenarios, an ensemble of multiple individual climate models is utilized to reduce uncertainty. The A1FI scenario ensemble consists of four different climate models: CCSM3 (USA), GFDL-CM2.1 (USA), HadCM3 (UK), and PCM (USA). The A2 scenario ensemble consists of ten different climate models: BCCR-BCM2.0 (Norway), CCSM3 (USA), CGCM3.1(T47) (Canada), CGCM3.1(T63) (Canada), CNRM-CM3 (France), ECHAM5/MPI-OM (Germany), ECHO-G (Germany/Korea), GFDL-CM2.0 (USA), HadGEM1 (UK), and PCM (USA). The B1 scenario uses the same ensemble as the A2 scenario. For each of these emissions scenarios, climate projection data was collected for three time periods: 2010 to 2039, 2040 to 2069, and 2070 to 2099. This was accomplished by utilizing modified scripts in MATLAB to pull the raw GDP projection data for the specified time periods. In addition, historical climate data was collected from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) from 1981 to 2010 to provide baseline historical data against which to compare the climate projections from the GDP as well as establish thresholds for extreme temperature and precipitation [17].

To produce climate projections specifically for the MARTA service area, a model in ArcGIS converted the data produced by the climate projections for each emissions scenario and for each time period into geocoded grid squares for Fulton and Dekalb counties (i.e. the MARTA service area). Finally, the averages of the temperature, precipitation, and extreme threshold values (established previously) were calculated for each grid square in both counties [17].

3.2 Interviews with MARTA Staff

After identifying the most significant climate stressors that are expected to intensify within MARTA's service area over the next several decades, in-person interviews were conducted with MARTA staff from the bus maintenance, track &

structures, civil engineering, architecture, rail vehicle maintenance, capital facilities, and transit asset management departments. The intent of these initial interviews was to learn from MARTA staff how the identified climate stressors had already begun to impact assets and operations, what assets and operations were most vulnerable to each climate stressor, and what efforts were planned or underway to address the impacts. Additional in-person interviews were conducted with MARTA rail and bus staff to identify locations that were expected to be particularly vulnerable to the identified climate stressors based on past experiences with extreme weather events. Maps of these vulnerable locations in MARTA's bus and rail network are found in Appendix A.

3.3 Visualizing Climate Stressors

As mentioned previously, some of the follow-up, in-person interviews conducted with MARTA staff sought to identify locations that would be particularly vulnerable to the effects of climate change. To better facilitate location identification for MARTA staff during these interviews, two maps were developed – one showing MARTA's bus network and one showing the rail network - for review and mark-up by MARTA staff. These two maps were developed in ArcGIS's ArcMap program using bus stop, rail line, and rail station geospatial location data provided by MARTA staff. In addition, a standard color legend was used to identify what type of vulnerability an identified location had (e.g. red indicated heat-related vulnerabilities). After the follow-up interviews, the markings made on the maps as well as notes taken during the interview were translated through the ArcMap program into digital notes and markings on each map. The final result was two maps that visualized (to the best of MARTA staff knowledge at the time) locations on MARTA's bus and rail networks that were expected to be vulnerable to the identified climate stressors based on prior experiences.

CHAPTER 4

CLIMATE CHANGE STRESSORS WITHIN MARTA’S SERVICE AREA

4.1 Introduction

Some material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

In order to make recommendations on how MARTA can integrate climate adaptation into its existing transit asset management system, it is important to first identify current and future climate “stresses” to MARTA’s service area. This chapter presents and discusses the results of two modeling approaches that were used to downscale and analyze existing climate change data to identify the most significant current and future climate “stressors” to the MARTA service area. This is a challenging task given that most climate models used to predict future conditions are really an ensemble of different models each using different assumptions on the underlying variables and relationships. In addition, the scale of analysis for climate modeling most often entails analysis cells that are hundreds of kilometers in size, often much larger than typical transit service areas. Thus, it becomes difficult to “downscale” climate data to a particular point in a service area as might be necessary to determine climate change-related risk to a particular asset. From a practical standpoint, the identification of potential stresses to transit agency assets and operations will have to be at a fairly general level. In addition to the two climate modeling approaches, information was also obtained from Dr. Michael Meyer on the ongoing National Climate Assessment initiative (much of the information in this initiative has not yet been released and thus the specifics as they relate to the Atlanta region and Georgia cannot be reported in this thesis) [18]. Generalized statements that have been discussed at public meetings are referenced in this report.

Information on historical climate hazards was also collected from meetings with MARTA maintenance staff. The chapter concludes by synthesizing the results from each of these sources to identify which climate stressors are expected to impact MARTA's assets and operations.

It is important to note that Atlanta will not experience sea level rise nor storm surge, given its location (two of the climate-related stresses that have received much of the attention of climate change researchers).

4.2 Results of GWRI Modeling Approach

The material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

Figure 4Figure 5Figure 6 show the average annual maximum temperature, average annual minimum temperature, and the average annual precipitation from 1972 through 2100, respectively, as projected by the initial modeling approach used by the GWRI. As noted in Chapter 3, this initial approach only utilized the A1FI "high" emissions scenario for its projections.

Figure 4 shows the annual average of maximum temperatures increasing through the end of the 21st Century, with upper boundary values moving from around 35 deg C (95 deg F) to about 40 deg C (104 deg F) by the turn of the century. Lower boundary values are also trending upward. The data also shows an increased range or higher variation in maximum temperatures over time. The observed and projected data indicate risks associated with high temperatures and possible heat waves, and higher fluctuations in temperature in the MARTA service area.

Figure 5 shows the annual average of minimum temperatures also increasing through the end of the 21st century, albeit at a lower rate than that of max temps. Lower boundary values of the annual average min temp show a change from freezing temperatures (0 deg C or 32 deg F) to a couple of deg C above freezing temperatures (or

35/36 deg F) by the end of the century. However, the data also shows a wider variation in minimum temperatures with several instances of annual min average temps falling below the freezing point. The observed and projected data indicates the possibility of risks associated with below freezing temperatures, as well as higher fluctuations in temperature, in the MARTA service area.

Figure 6 shows the lower boundary of average annual precipitation values trending downwards, indicating the possibility of more frequent droughts. Higher boundary values show fluctuations; however these fluctuations are within the range of values experienced over the past 40 years.

These findings indicate that possible climate hazards in the MARTA service area this century include *high temperatures* with the possibility of *heat waves*, *below-freezing temperatures*, *a wider variation or fluctuation in temperatures*, and *droughts*.

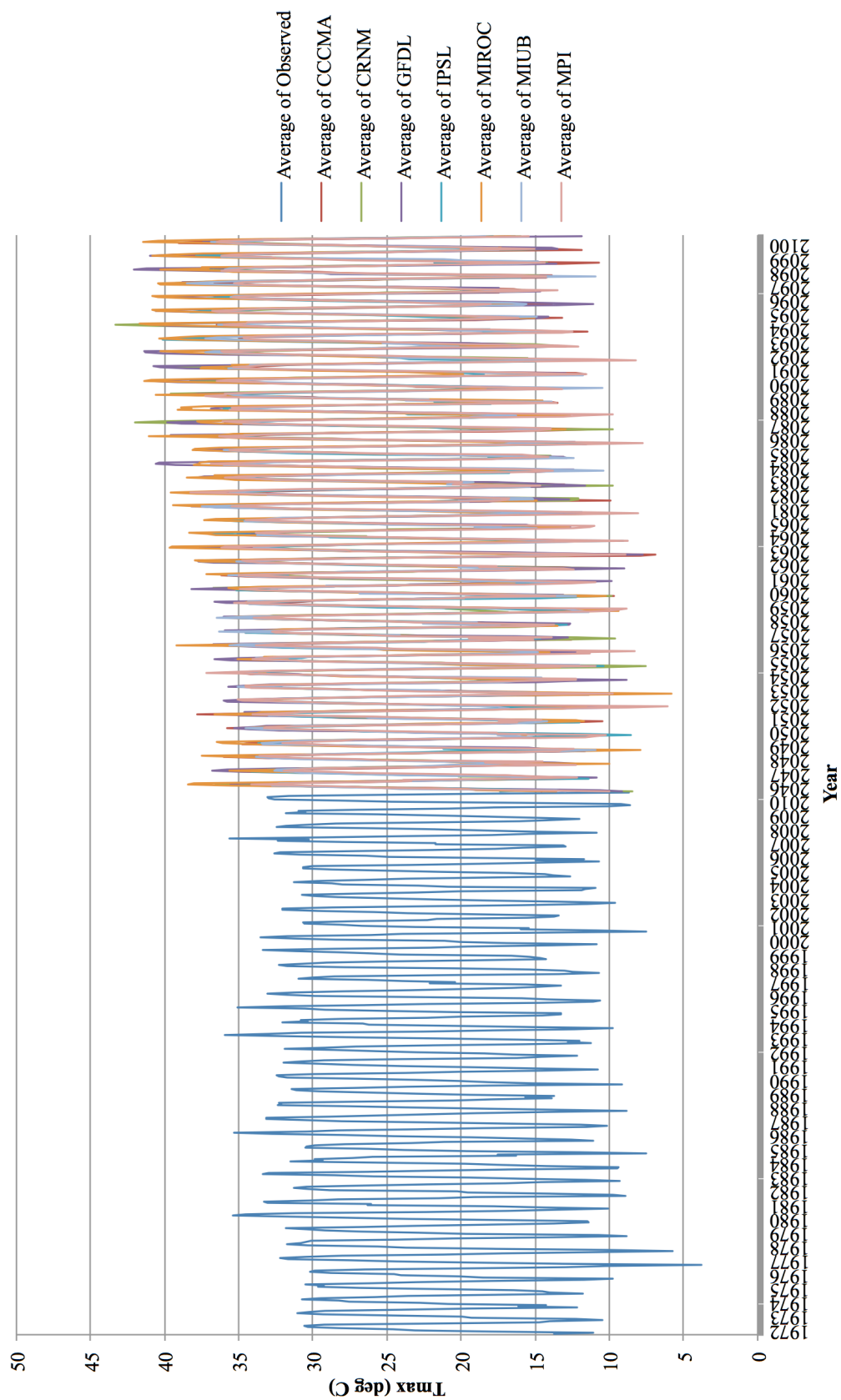


Figure 4: Average Annual Maximum Temperatures (Observed 1972 – 2010; Forecasted 2011 – 2100)
(Courtesy: GWRI)

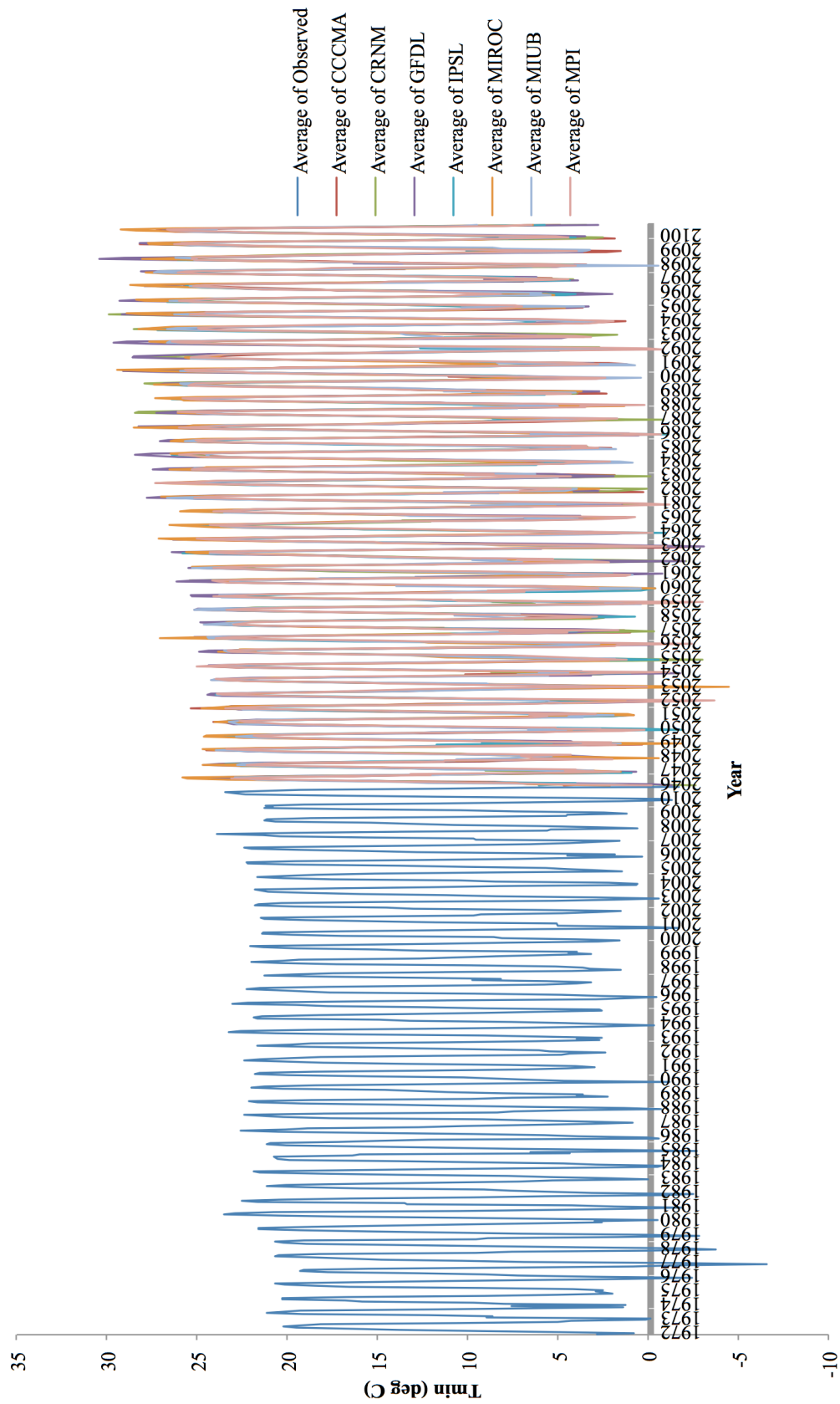


Figure 5: Average Annual Minimum Temperatures (Observed 1972 – 2010; Forecasted 2011 – 2100)
(Courtesy: GWRI)

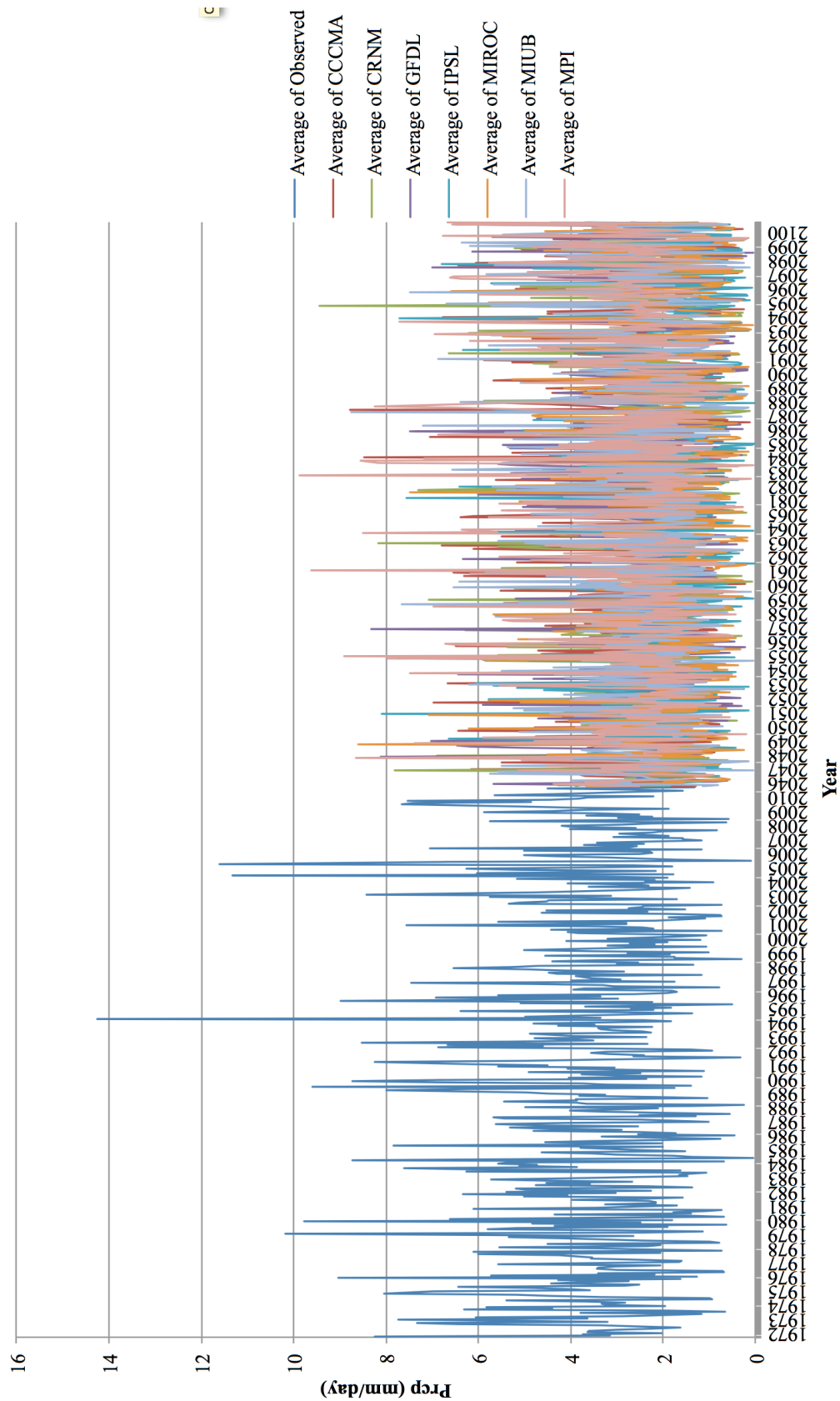


Figure 6: Average Annual Precipitation (Observed 1972 – 2010; Forecasted 2011 – 2100)
(Courtesy: GWRI)

4.3 Results of a Supplementary Climate Modeling Approach

Table 1 and Table 2 show the results of the more comprehensive modeling approach taken by O’Har (2013), which utilized the A1FI “high”, A2 “mid”, and B1 “low” emissions scenarios to project temperature and precipitation for the summer (June, July, and August) and winter (December, January, February) seasons for three time periods: 2010 to 2039, 2040 to 2069, and 2070 to 2099. Historical data from 1981 to 2010 was provided as a baseline for comparison and for establishing the temperature and precipitation thresholds analyzed (days over 90 degrees Fahrenheit, days with 1 inch or more of precipitation, etc.) [17]. Further detail on the methodology behind this approach can be found in Chapter 3 of this thesis. Considering the uncertainty of projecting climate conditions for such a localized area, only the general trends represented in these results should be analyzed and not the specific values for a particular time period.

Table 1. Atlanta Region Summer Temperature & Precipitation Projections [17]

Atlanta Region (Fulton and DeKalb Counties) Summer (June, July, & August) Temperature & Precipitation Projections				
A1FI Emissions Scenario Ensemble				
Time Horizon	1981- 2010	2010- 2039	2040- 2069	2070- 2099
Mean Temp °F	79.0	79.3	82.3	84.5
Mean Days Over 90°F	32.2	80.7	90.4	91.8
Mean Max Consecutive Days Over 90°F	N/A	39	82.0	85.7
Mean Days Over 100°F	0.4	1.23	7.41	20.7
Mean Max Consecutive Days Over 100°F	N/A	3.10	1.13	17.8
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	3.28	3.11	3.15
Mean Days with 1" or more precip	3.9	6.72	8.51	10.40
A2 Emissions Scenario Ensemble				
Time Horizon	1981- 2010	2010- 2039	2040- 2069	2070- 2099
Mean Temp °F	79.0	79.1	81.1	83.0
Mean Days Over 90°F	32.2	90.0	91.7	92.0
Mean Max Consecutive Days Over 90°F	N/A	75.7	82.5	91.0
Mean Days Over 100°F	0.4	6.59	20.0	45.5
Mean Max Consecutive Days Over 100°F	N/A	0.67	9.48	5.56
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	4.86	5.00	5.21
Mean Days with 1" or more precip	3.9	15.7	17.9	19.50
B1 Emissions Scenario Ensemble				
Time Horizon	1981- 2010	2010- 2039	2040- 2069	2070- 2099
Mean Temp °F	79.0	79.2	79.8	80.2
Mean Days Over 90°F	32.2	89.4	91.4	91.2
Mean Max Consecutive Days Over 90°F	N/A	74.8	91.0	88.0
Mean Days Over 100°F	0.4	8.85	11.2	16.5
Mean Max Consecutive Days Over 100°F	N/A	5.00	4.06	7.30
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	4.74	3.96	4.91
Mean Days with 1" or more precip	3.9	16.5	17.1	19.40

During the summer months, all scenarios show increases in mean temperature, with the A1FI scenario showing the most aggressive increases throughout the century. Mean days over 90 degrees Fahrenheit increase dramatically during the 2010 to 2039 time period across all scenarios, but then increase modestly over the rest of the century. Mean max consecutive days over 90 degrees Fahrenheit increase most aggressively under the A2 and B1 scenarios from 2010 to 2039, while most scenarios over the rest of the century show more modest increases. Mean days over 100 degrees Fahrenheit increase under all scenarios and at a more rapid rate over the century than mean days over 90 degrees Fahrenheit. With respect to precipitation levels, in general mean max daily precipitation levels increase over the century, with the exception of the A1FI scenario which projects a general decrease. In addition, all scenarios show an increase in mean days with 1 inch or more of precipitation over the century.

These results suggest that the summer months will generally experience higher average temperatures as well as more frequent and prolonged extreme temperatures. In addition, precipitation will increase in both volume and intensity.

Table 2. Atlanta Region Winter Temperature & Precipitation Projections [17]
Atlanta Region (Fulton and DeKalb Counties) Winter (December, January, & February) Temperature & Precipitation Projections

A1FI Emissions Scenario Ensemble				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	45.0	46.7	48.8
Mean Freezing Days (Low ≤ 32°F)	30.6	80.8	76.4	70.3
Mean Max Consecutive Freezing Days	N/A	36.7	38.7	30.5
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	4.21	4.55	5.06
Mean Days with 1" or more precip	3.6	11.7	10.6	11.2
A2 Emissions Scenario Ensemble				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	45.1	46.5	48.6
Mean Freezing Days (Low ≤ 32°F)	30.6	89.2	88.6	86.8
Mean Max Consecutive Freezing Days	N/A	83.5	65.7	55.2
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	3.66	3.84	3.84
Mean Days with 1" or more precip	3.6	24.5	25.4	26.6
B1 Emissions Scenario Ensemble				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	44.9	45.9	46.4
Mean Freezing Days (Low ≤ 32°F)	30.6	89.2	89.0	88.4
Mean Max Consecutive Freezing Days	N/A	60	86.5	74
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	3.76	4.39	4.61
Mean Days with 1" or more precip	3.6	24.9	25.4	27.2

During the winter months, all scenarios project an increase in mean temperature over the century, though not as significant an increase in the summer months. The number of freezing days (with a low temperature of 32 degrees Fahrenheit or less) increases dramatically from 2010 to 2039, but then has slight decreases for the rest of the century under all scenarios. While the total number of freezing days generally increases over the century, the mean maximum number of consecutive freezing days generally decreases over the century, though some scenarios show increases from 2040 to 2069. With respect to precipitation, mean max daily precipitation levels generally increase over the century, with the exception of the A2 scenario, which projects a slight decrease. In addition, the mean number of days with 1 inch or more of precipitation increases dramatically for all scenarios initially (especially A2 and B1), but then remains relatively constant for the rest of the century.

These results suggest that the winter months will generally become warmer over time, albeit at a less aggressive rate than mean temperatures in the summer months. This indicates that the region will experience a wider range of temperatures over the course of any given year. In addition, while the mean temperature during the winter will generally increase, the frequency of extremely cold days will also increase, though they will not be prolonged. Finally, with respect to precipitation, the winter months will experience a significant increase in total precipitation, though the intensity of the precipitation will only increase slightly.

The results of this supplementary modeling approach for the summer and winter seasons affirm and clarify the results of the initial modeling approach conducted by the GWRI. Under most emissions scenarios, the region will experience increases in mean temperature, the frequency and duration of extremely hot temperatures, the frequency (but not duration) of extremely cold temperatures, and the volume and intensity of precipitation.

4.4 National Climate Assessment Initiative

The material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

The national climate assessment effort is a Congressionally mandated initiative to identify the key climate-related trends that will affect the United States. An update of the current plan is underway with a final update to be published in 2013. This final effort will most likely represent the latest thinking on what types of climate change stresses are likely to affect the United States by region and by sector. Transportation is one of the sectors being examined and the southeastern United States is one of the regions that will be in the final report. Because of the peer review process being used in the development of this report, preliminary conclusions and observations cannot be shared in this thesis. However, many of the observations and conclusions mirror those that have been published and printed in the literature so they will be no surprise. For example, much of the climate science that has examined both historical and future climate conditions concludes that climate changes will continue to occur past 2100. Average temperature, which has been reported as having risen 1 degree Fahrenheit over the past century is expected to continue to rise. Along with the increase in average temperature, the number of higher-intensity precipitation storms is expected to increase across the country. Although the science associated with extreme weather events such as extreme heat and extreme cold spells is not as developed as the science focusing on average changes in climate, most climate scientists believe that the occurrence of such extreme weather events will likely increase in the future.

The southeastern United States has a wide range of potential climate change impacts. It has already experienced the largest number of billion dollar weather/climate disasters of any U.S. region from 1980 to 2011: these being primarily floods, hurricanes and large-scale tornado outbreaks. Historical data show that the numbers of days with high temperatures exceeding 95°F and low temperatures below 75°F have increased and

the number of extremely cold days has declined since the 1970s. The numbers of extremely wet and extremely dry summers have increased. In addition, while the assessment does not project an increase in the frequency of droughts, it notes that population growth and land-use changes will exacerbate water availability in the region when droughts do occur. Rainfall intensities have also increased for both daily and 5-day periods. From 1958 to 2011 the number of high-intensity rainfall events in the southeast increased by 27 percent [18].

In the future, average temperatures in the southeast are expected to increase: some place this increase as an average 2 to 6 degrees Fahrenheit within 40 to 50 years in interior Georgia. By 2100, the southeast is expected to have the largest increase in heat index (the temperature as the human body experiences it) of any other region in the nation [19]. With respect to precipitation, the north Georgia region is expected to see increases in average precipitation, whereas other parts of the region will likely see decreases, continuing a trend in drought conditions that has characterized the south for many years. There is less certainty associated with precipitation forecasts than with temperature simply because of the more complex meteorological relationships that cause precipitation levels to change over time. Lower-intensity hurricanes are expected to decrease in number and higher-intensity hurricanes (which can result in large peripheral rainfall in the Atlanta region) are expected to increase along the eastern and Gulf coasts.

In summary, although not official, the preliminary observations of the National Climate Assessment effort confirm the forecasts that have been done by independent researchers and climate scientists for the southeast and, in particular, likely implications for the Atlanta region. Average temperatures will be higher, extreme temperatures will be higher and last for longer periods of time, higher intensity rainfall will likely occur in more concentrated storm events, average precipitation will increase (although this is less certain and varies by area in the southeast), and droughts, while not necessarily more frequent, will have a greater impact as the region's population grows.

4.5 Potential Impacts of Climate Change on MARTA's Assets and Operations

The material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

From discussions with MARTA staff on examples of weather-related incidents that have affected operations in the past, two climate stressors stand out as most significant to MARTA's assets and operations.

4.5.2 Higher Extreme Temperatures for Longer Periods of Time

The consensus of the analysis efforts reviewed indicate that the Atlanta region will experience higher temperatures on average over the next 70 to 80 years, but that it will also experience longer periods of extreme temperatures, defined as greater than 95 degrees Fahrenheit (i.e., possible heat waves). This could potentially affect MARTA operations in two major ways. First, the high levels of heating of key electrical instrumentation (signals, communication relays, passenger information systems, etc.) could lead to a higher level of failure of these devices. Second, heat-related passenger and worker comfort could become a more important factor in how MARTA schedules and protects its labor force, and the way it assures a comfortable experience to its passengers. Given that climate modeling is much more precise with respect to temperature (than precipitation); there is a high likelihood that this climate stressor will indeed occur over the next many decades. In addition, it will be important to consider how higher fluctuations in temperatures can affect MARTA operations and assets.

4.5.2 Higher-Intensity Precipitation in Storm Events

As noted earlier, the forecasts for average precipitation levels in the MARTA service area are less certain than forecasts for temperature increases. However, most scientific studies have concluded that the number of higher-intensity storms will likely increase in future decades, with this particularly being the case in the southeastern United

States. MARTA has experienced some flooding in several track and facility locations from intense storms over the past several years. It is likely that with a larger number of intense storms expected in the future, more flooding will occur. Many of MARTA's most critical assets have been built in such a way that flooding from nearby creeks, streams or drainage facilities will not affect operations. However, there are some assets where potential flooding risks do exist, and for bus operations on local streets and roads, the interruption of service due to the flooding of these facilities will impact service provision.

Another implication of higher-intensity storms relates to the design and maintenance of drainage facilities, primarily culverts, channels and retention ponds. One of the lessons learned in Vermont from Tropical Storm Irene was that poorly maintained culverts, that is, culverts blocked by debris and other material that substantially reduce the flow capacity, were primary reasons for road failures. For long-lived MARTA assets in high runoff areas where drainage capacity has been designed taking into consideration historical data, the risk of overflow and runoff backup into service-sensitive areas (given higher-intensity downpours) could be an important vulnerability.

One aspect of this climate variable that is nearly impossible to forecast is the potential damage caused by high winds often associated with high-intensity storms. There has not been any research or study at this time that has attempted to forecast high wind events associated with more intense storms. Maintenance personnel at MARTA also did not have any memory of high winds causing significant damage to MARTA assets.

4.6 Summary

The material in this section is reported from the following document: Task 1: Draft Technical Memorandum [16].

Climate-related forecasts for the MARTA service area in the Atlanta metro region indicate increased likelihood of higher temperatures with heat waves, below-freezing

temperatures, a wider variation in temperatures, and droughts. More general climate-related forecasts for the Atlanta and North Georgia region also indicate that average temperatures will rise from now to 2100; and the range in high to low temperatures will likely increase. The more general information also indicates the possibility of flooding from high-intensity precipitation, as well as higher-intensity tornadoes. Finally, meetings with MARTA staff indicate that higher extreme temperatures for prolonged periods and more intense precipitation during storm events are their most significant concerns.

The implications of this climate change assessment is that those assets most vulnerable to **flooding** (at lower elevations near streams or creeks, or which depend on well-maintained drainage systems to remove runoff from the facility), and those whose performance can be affected by **longer exposures to higher temperatures**, as well as a **wider variation in temperatures** (signal and communications equipment and perhaps tracks and pavements) are those in most need of monitoring. MARTA will also need to consider the implications of **droughts** on agency operations and assets.

CHAPTER 5

THE IMPACT OF CLIMATE STRESSORS ON MARTA ASSETS AND OPERATIONS

Most of the material in this section is reported from the following document: Task 2: Draft Technical Memorandum – Characterization of Climate Change Risk on Agency Assets and Operations [20].

5.1 Introduction

This chapter characterizes the risk of climate change on MARTA’s infrastructure and operations by identifying assets, operations, and locations within the bus and rail network that are most vulnerable to the climate change stressors that were identified in Chapter 4: longer periods of extreme heat (>95F), wider variations in temperature, more intense precipitation during storm events that could result in flooding, droughts, and more intense wind events from either storms or tornadoes

To accomplish this task, several interviews were conducted with MARTA staff to learn about both how these climate stressors are currently affecting MARTA’s assets and operations as well as how they may impact assets and operations in the future as these stressors intensify. This chapter presents the results of these interviews for each department involved in MARTA’s asset management program: bus maintenance, rail vehicle maintenance, track & structures, capital facilities, and architecture. The chapter also includes related information from MARTA’s Risk Management unit. Finally, the chapter provides several conclusions on which climate stressors appear to have the greatest overall impact to MARTA assets and operations, as well as which asset groups appear to be the most vulnerable to each climate stressor. The results of the interviews with MARTA staff were summarized in a matrix that can be found in the Appendix B.

5.2 Climate Change Impacts to MARTA’s Infrastructure & Operations

5.2.1 Bus Maintenance

MARTA's bus maintenance department is responsible for the maintenance of 531 buses, 187 paratransit (MARTA Mobility) vehicles, and approximately 400 non-revenue vehicles, such as MARTA police cars and administrative vehicles. The department has several maintenance facilities that are able to perform almost every task required to maintain the vehicle fleet, from daily bus washing and interior cleaning to engine and component rebuilds or replacements.

The climate stressor that has the greatest current and long-term impact to the bus maintenance department's assets and operations is the increasing frequency of days with **extreme heat**. With respect to the bus maintenance facilities, extreme heat days can pose a health risk to employees working on vehicles in the shop, since most shop areas do not have Heating, Ventilation, and Air Conditioning (HVAC) systems (because most are large and open to the outside) and the facilities are built mostly out of concrete, which absorbs and retains heat for long periods of time. With respect to assets, MARTA utilizes many Compressed Natural Gas (CNG) buses in its fleet, which have engines that operate at a very high temperature under normal conditions. Periods of extreme heat can cause engine components to overheat and fail. In addition, HVAC systems for all bus types can fail during periods of prolonged extreme heat due to longer operating cycles. The bus maintenance department is addressing this issue by making sure to monitor all bus HVAC systems more closely during summer months. In addition, newer buses have been outfitted with an electric cooling system instead of a hydraulic cooling system, which reduces parasitic load on the engine, thereby increasing fuel efficiency and reducing emissions. MARTA was the first transit agency to switch to an electric cooling system for its bus fleet. Future updates to the bus fleet include an updated version of the electric cooling system that will utilize a variable thermostat and a variable-speed electric water pump, replacing the current hydraulic HVAC system with an electrically operated one, and employing a different battery charging system that utilizes regenerative braking and

newer battery technologies. The electrification of these bus components could increase the fuel efficiency of each bus by 25%.

There are several other climate stressors and weather events that have an effect on MARTA's bus maintenance department. The weather event that has the most significant short-term impact to the bus maintenance department, but is relatively infrequent, is an **ice storm**. The reason for this is because Atlanta normally experiences relatively mild winters compared to the rest of the country. Therefore, there is not a significant amount of resources available locally to protect the city of Atlanta and the MARTA bus network when an ice storm does occur. The result is that most bus service and maintenance work comes to a halt until the ice melts. However, after the snow and ice event that occurred in January of 2011, MARTA acquired tire chains for its buses, snow plows, and sand spreaders in order to try and provide for at least a minimum level of bus service when the next ice storm arrives.

A climate stressor that has had a more indirect impact to MARTA's bus maintenance operations has been the recent increase in **drought** conditions. During these conditions, MARTA has to reduce the frequency of their bus washing due to the amount of water required. However, MARTA is addressing this issue by installing new bus washing racks that will reduce water use by 90% through the use of water from reclamation systems.

The climate stressors identified (or their corresponding weather events) can also cause **local or widespread power outages**. Unfortunately, these local power outages cause MARTA's bus maintenance facilities to shut down because the backup generators currently in place are not powerful enough to provide electricity to the entire facility and its equipment. This is a serious concern because these facilities are important to the larger Atlanta metro area during emergencies (of any type) because of their ability to sustain other support systems such as fire departments and police forces. MARTA is currently

trying to procure larger generators to install so that the facilities will be able to operate independently during emergencies.

Interestingly, there are several climate stressors that do not appear to have much of an impact on bus operations or assets. With respect to the prospect of wider variations in temperature, MARTA staff noted that nearly all transit buses produced in North America are designed to operate within a very wide range of environmental conditions, and are therefore inherently resilient to wide variations in temperature. More intense precipitation during storms is also not a serious concern, since most bus routes do not travel through areas prone to flooding. Finally, more intense wind events are not an immediate concern because of the very rare occurrence of tornadoes in MARTA's service area.

5.2.2 Rail Vehicle Maintenance

The rail vehicle maintenance department is responsible for the maintenance of MARTA's fleet of heavy rail vehicles, which are serviced at either Armour Yard or Avondale Yard.

Like the bus maintenance department, the climate stressor that has the greatest current and potential long-term impact to the rail vehicles and their maintenance is the increasing frequency of days with **extreme heat**. According to MARTA staff, the heat waves experienced during the summer of 2012 were particularly intense and caused more issues than in prior years. The periods of extreme heat caused the HVAC systems installed on the rail vehicles to operate for longer than normal, which resulted in an increase in the number of failures. This in turn resulted in more customer complaints about the conditions inside the rail vehicle than normal. Extreme heat can also be an issue for MARTA staff that work within the maintenance facilities, since it is not cost-effective to provide HVAC coverage for the large and open rail maintenance facilities. However, there are several procedures in place (some mandated by the Occupational Safety and

Health Administration (OSHA)) to reduce the risk of heat exhaustion and heat stroke for employees: water and Gatorade/PowerAde are available at all times in the facilities; employees are given more work breaks during hot days, and information is provided to employees on how to identify and treat victims of heat exhaustion and heat stroke.

While cold temperatures by themselves do not have much of an impact on MARTA rail vehicles or operations, the **ice storms** that can occur during cold conditions can have a significant impact on MARTA's rail operations. Despite the cover that is in place over the third rail, ice can still form on the top of the rail, thereby preventing MARTA rail vehicles from receiving the electricity they need to operate. Therefore, before potential ice storms or during icy conditions, MARTA will run rail vehicles that have ice-scraping collector shoes to prevent the build up of ice. If the third rail does become covered in ice, MARTA has modified rail vehicles that can spray deicing fluid on the rails (both running rail and the third rail). However, this operation requires significant time and resources to clear the rails, as well as poses a safety hazard to MARTA employees.

Since the MARTA rail network is mostly located either on natural ridges or aerial structures, **flooding** as a result of intense precipitation during storms has not been a major issue for rail vehicles. However, the rail maintenance facilities (particularly Armour Yard, which is located near a large creek) must be shut down if they are flooded because of the risk for electrocution to employees from the high-voltage equipment located within the facilities. In addition, during intense precipitation events, train operators may operate the train in emergency braking mode if they feel the train is not stopping properly. Unfortunately, this operation mode can cause damage to the wheels through the creation of small flat spots on the wheel as it slides (instead of rolling) along the track.

Another climate stressor that is not as predictable, but can still cause damage to rail vehicles, is **intense wind** caused by storms or tornadoes. These events normally result in flying debris that can damage exposed rail vehicles. In addition, MARTA's

communication antennas are installed on skyscrapers in downtown Atlanta and on top of Stone Mountain. These antennas could be damaged or destroyed during events such as the tornado that damaged many buildings in downtown Atlanta in the spring of 2008. The loss of these antennas would disrupt MARTA's entire communications network, thereby disrupting rail (and bus) service even if MARTA's assets were unharmed.

There are two other climate stressors that do not appear to have much impact to MARTA's rail vehicles or their operation. Recent **droughts** required rail vehicle washing to be reduced, but they are not considered an immediate concern. **Wider variations in temperature** do not have much of an impact on the rail vehicles or their operation, but rather on patrons, who have different tolerances for a comfortable range of temperatures.

A noteworthy side effect of these climate stressors and weather events is the effect they have on **vegetation** located on or near the rail right-of-way. Vegetation has been an issue for MARTA because it can obscure the vision of train operators as the vehicle travels along the rail. The ice storms, intense wind, or tornadoes that cause the vegetation to fall can also cause damage to the vehicles.

5.2.3 Track & Structures

MARTA's track and structures department is responsible for the maintenance of running rail, switches, aerial track structures, and (to a lesser extent) MARTA rail stations.

According to MARTA staff, the climate stressor that will cause the most persistent problems for rail is **extreme heat**. This is because prolonged periods of extreme heat (or one unseasonably hot day) cause rail lines to expand and eventually buckle under the weight of heavy rail vehicles if not managed properly. As mentioned before, the heat waves experienced during the summer of 2012 were particularly intense and prolonged; however, there were no significant disruptions to rail service due to issues with the rail during this period. This is because of two reasons. First, Federal Railroad

Administration (FRA) regulations require that every section of track must be walked and visually inspected twice per week. Second, MARTA has a very specific and stringent set of standards in place for the maintenance and replacement of its rail lines. In addition, the department is usually able to fix any significant rail problems during non-peak periods to minimize the disruption to rail service. To a lesser extent, **wide variations in temperature** can also be stressful on the rail if they occur over several days.

Similar to the rail vehicle maintenance department, the track and structures department can also experience significant impacts to their assets and operations during **ice storms**. Again, the main concern for the department is the potential freezing of the third rail that can occur during these storms, which can severely disrupt MARTA rail service. While the rail vehicle maintenance department does have several modified rail vehicles for deicing, they are not able to operate farther than the nearest third-rail power source. If there is extensive freezing of the third rail, the track and structures department has modified trucks that can travel along the rail lines while employees spray deicing fluid on the third rail. However, this procedure is very time, labor, and otherwise resource-intensive, and can also pose a safety hazard to employees through the potential for falls due to icy surfaces. Because of this, MARTA track and structures staff has emphasized the importance of continuing to run trains at frequent intervals during icy conditions to prevent the third rail from freezing over.

As mentioned previously, MARTA's rail network is mostly located away from local floodplains and above most major rivers or streams. However, issues with **flooding** can arise due to **intense precipitation** during storms as well as groundwater. With respect to intense precipitation, flooding can result when drains and pipes near tunnel openings or on aerial structures (most notably the Georgia State/Garnett interline connector tunnel) become clogged by debris and/or overwhelmed by the volume of water runoff from these storms. With respect to groundwater, there are several stations (most notably Arts Center) that require sump pumps to run constantly to prevent local

groundwater from flooding the tracks. This is not an issue that is directly related to the climate change stressors that have been identified, but is important because of its potential impact to MARTA rail service.

MARTA track and structures staff also mentioned the impact **vegetation** can have on their assets and operations. Similar to what has been discussed previously, vegetation near the right of way can fall over due to intense storms, wind, or ice events and block the track. Vegetation can also become a fire hazard during **drought** conditions due to the electrical arcs that are sometimes created between rail vehicle collector shoes and the third rail. The track and structures department has brush cutters that can trim back the vegetation, but their operation requires coordination with several other maintenance departments and significant time on the track right of way.

The direct effects of **intense wind** and **tornadoes** have not been a critical issue for most track and rail infrastructure, with the exception of the King Memorial station. This station experienced significant damage as a result of the tornado that traveled through downtown Atlanta several years ago. The reason this station is particularly vulnerable to these effects is because it is the highest elevated station on the MARTA rail network and is surrounded by mostly flat, uncovered ground.

5.2.4 Architecture

MARTA's architecture department is responsible for the roofs, landscaping, platforms, and art installations at MARTA rail stations. Many of the issues the department has with its assets are primarily a result of the general aging of the system, though factors such as climate change stressors, patron abuse, and poor installation could have compounded the aging factor over time.

One of the most critical concerns for the architecture department is the poor state of repair of the many roofs in MARTA rail stations. Many of the older (original) roofs that are still in place have almost no pitch, which causes water (or snow and ice) to pool

on the roof during **intense precipitation** events (or **ice storms**). This results in significant, prolonged stress to the roof structure after the storm has passed, shortening the life span of the roof over time. In addition, **vegetation** can cause damage to the roofs with falling leaves, which clog drains and deteriorate the roof material. Falling limbs may also damage the roof structure. The most critical need in this system has been the roof in the Arts Center station, which was in dire need of replacement for several years, but a lack of funding (until recently) had prevented it from being replaced. It is now the only active roof replacement project in the entire MARTA network. When a roof is replaced, in addition to incorporating some degree of pitch into the new roof structure, MARTA primarily uses metal because it is better able to withstand the effects of weather over time and requires almost no maintenance after installation.

With respect to customer comfort and safety, **extreme heat** and **intense precipitation** can have a significant impact at and approaching bus stops (and to a lesser extent rail stations) that lack sufficient shelter and shade from the elements, whether natural (i.e. vegetation) or manmade (i.e. bus shelters).

With regards to landscaping, **droughts** have had a significant impact in recent years. MARTA has attempted to install hardier, local, drought-resistant plants around station areas, but a combination of continued extreme drought conditions and patron abuse has caused the new plants to struggle.

An issue for many rail station platforms has been the deterioration of the pavers over time due to a combination of age, weather, and poor installation. Specifically, intense freeze-thaw cycles several years ago resulted in the poor platform conditions that exist today. The architecture department does have a small program that replaces the most deteriorated sections of the platforms, but (similar to roof replacements) there is not enough money to replace entire platform surfaces with new material.

A recent art restoration project at the North Avenue station emphasized how safeguards that are implemented when an asset is replaced can extend the life of the asset.

This restoration project involved repainting several large murals in the station that had faded over many years. In addition to the repainting, a UV film was placed on a skylight that provided natural light into the station, but also caused sunlight to strike some of the murals directly. This film will help prevent the paint from fading as quickly as it did when it was originally placed.

5.2.5 Capital Facilities

The capital facilities department is responsible for the overall maintenance and upkeep of MARTA's entire infrastructure network. Therefore, many of the earlier discussions on how climate change stressors are affecting specific MARTA assets and operations were echoed in a more general sense by capital facilities staff.

As has been mentioned several times in this chapter, the most critical ongoing concern for MARTA is the effect of **extreme heat** on assets, operations, personnel, and patrons. This stressor is followed by **intense precipitation** events that can cause flooding in tunnels due to clogged drains or overwhelmed pipes. In addition, there are several areas in MARTA's network, such as near the Medical Center station that has steep slopes near the rail right of way, which can deposit mud (in addition to water) on the rails during heavy rains. **Intense wind events and tornadoes** can cause vegetation located near the rail right of way to fall onto the tracks or passing rail vehicles, causing damage to those assets and impacting MARTA rail operations. **Droughts** can impact the washing of bus and rail vehicles, as well as cause vegetation to become a greater fire hazard. Finally, **wider variations in temperature** can cause stresses on rail lines, but are usually only a concern if the conditions persist over several days.

An interesting point that was made by MARTA staff was that the feeder system design that MARTA uses, in which the bus network delivers patrons to the nearest rail station, can present challenges during severe weather conditions because of the reliance of both systems on each other and their differing vulnerabilities to weather events.

Another point made was that MARTA should not only consider the cost of an asset when it fails (whether due to climate stressors or simple age), but the cost of lost revenue when the failed asset affects MARTA service.

5.3 MARTA's Risk Management Program

MARTA's risk management department handles all of MARTA's insurance claims and therefore acts much like a small insurance company. The original MARTA Act guides how the agency manages risk. Because MARTA is a quasi-government agency, it does not have sovereign immunity unlike most other agencies that were created by an act of the Georgia legislature. In addition, several corridor agreements were made around the time of MARTA's creation between MARTA and the railroad companies that operated along those corridors. Both of these factors mean that the agency must insure itself against the possibility of events that can cause damage to the system itself, the employees that maintain and operate it, and the patrons who utilize it. The agency currently has approximately \$145 million in insurance coverage with a retention of \$5 million. This means that MARTA is self-insured on insurance claims for damages up to \$5 million, above which private insurance companies become involved. Fortunately, MARTA has not experienced any event that has caused extensive damage to the system. The recent damage done by the tornado that occurred in downtown Atlanta in 2008 to MARTA facilities cost approximately \$150,000.

According to MARTA staff, while the agency is aware of the risks related to climate change, climate change risk is not considered as serious of a concern to the system compared to the risk of terrorism, other security risks, liability risks, auto liability risks, risk of injury to patrons, and risk of injury to employees. With specific regard to the risk of terrorism, since MARTA is a Tier 1 transit agency it must conduct various security drills for the Federal Transit Administration every year.

5.4 Conclusions

The interviews conducted with MARTA staff provided valuable insight on how the different climate change stressors identified in Chapter 4 impact MARTA assets and operations currently and potentially in the future.

The climate stressor that seems to have the greatest overall impact on MARTA assets and operations, in both the short-term and long-term, is **extreme heat**. This climate stressor can cause bus and rail vehicle components to overheat and fail, rail lines to expand and eventually buckle, and safety concerns for MARTA employees operating either outside or within maintenance facilities, and MARTA patrons using the system. Another climate stressor that can cause significant impacts is **intense precipitation** and the **flooding** that can result from either clogged drains or overwhelmed pipes (and possibly as the result of failed sump pumps that cause groundwater to seep in). This stressor can cause rail lines to become flooded near tunnel entrances and mud to runoff onto the tracks where there are steep slopes. In addition, older roofs that do not have pitch experience significant stresses to their structure due to the pooling of water (or snow and ice) that remains for long periods after these events. As has been mentioned, while the MARTA rail and bus network is generally located away from local floodplains, there are still several areas that are vulnerable to flooding, most notably the Georgia State/Garnett interline connector tunnel. A climate stressor that has not been as frequent, but has the potential to cause damage to assets and disruption to service is **intense winds** or **tornadoes**. This stressor can cause vegetation near the rail right of way to fall onto the tracks or passing rail vehicles and damage or destroy radio communication antennas. It has also cause damage specifically to the King Memorial station, which is surrounded by open ground and is the highest elevated station on the network. To a lesser extent, **droughts** have had a more indirect than direct impact on MARTA. This stressor can cause vegetation near the right of way to become a potential fire hazard, reduced vehicle washing, and recent landscaping improvements to struggle. Also, **wider variations in temperature** do not have as significant an impact on assets unless the conditions are

prolonged. However, it can cause discomfort for MARTA patrons who have different tolerances with respect to their comfortable range of temperatures.

The weather event that appears to have the most significant short-term impact to MARTA operations, though it is relatively infrequent, is an **ice storm**. This event impacts MARTA operations in several ways. First, if trains are not run frequently during icy conditions, the third rail can freeze over, which causes significant delays to rail service until either modified rail vehicles or trucks can reach the affected areas with deicing equipment. Second, if roads became covered with ice, in the past MARTA bus operations would completely shut down. However, MARTA acquired bus tire chains after the most recent ice storm event to provide for at least a minimum level of service. Third, vegetation covered in ice can fall down on tracks or passing rail vehicles. Finally, icy conditions themselves pose a safety risk for MARTA employees that have to travel around the system to prevent or remove ice buildup.

CHAPTER 6

CLIMATE ADAPTATION STRATEGIES FOR MARTA

6.1 Introduction

Utilizing the findings of the previous two chapters, which identified the climate stressors that are expected to impact MARTA's service area (Chapter 4) and assets, operations, and locations in the MARTA network that are vulnerable to these stressors (Chapter 5), this chapter identifies climate adaptation strategies that could be implemented in each department at MARTA for each of the five major climate stressors identified in Chapter 4. These strategies are further divided into short-term strategies that could be implemented within the next few years and long-term strategies that could be implemented over a longer time period (such as during major capital replacement or rehabilitation efforts). While MARTA has already begun to address climate change indirectly through some of its efforts as discussed in Chapter 5, there are still many areas that can be considered for climate change adaptation measures. A matrix that summarizes the strategies discussed in this chapter can be found in Appendix C.

6.2 Bus Maintenance & Operations

6.2.1 Heat Waves

6.2.1.1 Short-Term Strategies

To address the high operating temperature of CNG bus engines and longer operating times for air conditioning systems during extremely hot days, MARTA can develop a policy that establishes temperature thresholds at which more frequent inspections are conducted for CNG buses and air conditioning systems on all buses.

To better protect employees from the threat of heat exhaustion and heat stroke, MARTA could evaluate its existing policies on bus maintenance worker safety during hot

days and update or clarify these policies as necessary to ensure their safety. This update could include establishing temperature thresholds at which specific actions are taken to protect bus employees from heat-related illnesses.

The agency could also consider the effects of heat on its customers. The agency could seek to educate customers on techniques for staying cool when waiting at a bus stop during extremely hot days, as well as utilize what resources it currently has available to keep stop areas cool. The agency may consider upgrades to bus stops where passengers do not have protection from extreme heat and rain.

6.2.1.2 Long-Term Strategies

Before beginning the process for procuring new buses, MARTA could consider updating its design standards to include heat-resistant materials where feasible, more efficient and durable engine cooling systems (especially for CNG buses), and more durable air conditioning systems.

To improve employee safety during hot days, the agency may consider installing additional air conditioning systems at its maintenance facilities where feasible. If air conditioning is not feasible for certain areas (such as large, open shop floor areas), the agency may also consider retrofitting its existing facilities and update design standards for new facilities to utilize natural airflow to keep the temperatures cool enough for employees to work safely.

6.2.2 Flooding from More Intense Precipitation During Storms

6.2.2.1 Short-Term Strategies

While MARTA's rail network is generally located out of known floodplains, the agency could seek to identify all flood prone areas within its bus route network. In addition, the agency could ensure that its bus storage facilities are above the most current

floodplain levels. If they are not, the agency should consider identifying temporary storage locations for buses that could be used if flood conditions are expected.

In order to ensure that the interruption to bus service is minimal during flood conditions, MARTA could establish a bus-rerouting procedure for flood prone areas, along with a communication plan to inform affected customers about changes to bus service.

With respect to bus storage and maintenance facilities that are located within a floodplain or other flood prone area, the agency could establish a combined emergency shutdown and facility restart plan for each facility and practice the plan with employees who operate out of or within those facilities.

6.2.2.2 Long-Term Strategies

If certain bus routes have chronic issues with flooding that forces re-routing, the agency could consider developing an alternative route plan for all flood prone bus routes that can be utilized in the event of flooding. This plan should be communicated to affected customers along these routes when it is established and every time it comes into effect during flood conditions. MARTA could also seek to incorporate more redundant routing into its future bus plans so that the re-routing of a single bus during flooding does not severely limit a customer's accessibility to the system.

When feasible, the agency may consider relocating bus storage and maintenance facilities away from flood prone areas. If relocation is not feasible, the agency may consider either hardening these facilities against the threat of flooding or abandoning them.

6.2.3 Droughts

6.2.3.1 Short-Term Strategies

While drought conditions in recent years have forced the agency to reduce bus washing through local water-saving ordinances, the agency could establish its own bus-washing plan for various levels of severity of drought conditions.

6.2.3.2 Long-Term Strategies

Recent drought conditions have also resulted in the agency replacing some of its bus washing equipment with more water-efficient systems that use low-flow heads and reclaimed water. The agency could consider replacing all of its bus washing facilities with these systems in the long-term. In addition, these systems can further reduce water usage by utilizing non-potable sources of water for washing, such as local groundwater or rain barrels. The agency may also investigate if there are paints or coverings that could be applied to buses that reduce the frequency of washing, regardless of drought condition.

6.2.4 Wider Temperature Variations

6.2.4.1 Short-Term Strategies

While most transit buses produced in North America are designed for a wide range of operating environments, MARTA could consider establishing temperature thresholds for increased inspection of bus engine cooling systems for both extremely hot and cold days. The agency may also investigate the impacts of wider temperature ranges on bus tire pressures, which could affect the lifetime of the tires and the performance of the bus.

6.2.4.2 Long-Term Strategies

In addition to incorporating more heat-resistant materials in its bus design standards (as discussed previously), the agency could also consider incorporating materials that are able to withstand greater temperature ranges.

6.2.5 More Frequent High-Wind Events

6.2.5.1 Short-Term Strategies

Similar to flood prone areas and heat waves, MARTA could consider establishing wind velocity thresholds at which bus service is re-routed away from the most vulnerable areas or suspended entirely.

6.2.5.2 Long-Term Strategies

When feasible, the agency could harden bus facilities and routes that are most vulnerable to high winds. In addition, bus storage facilities could be hardened to prevent damage to buses and injury to passengers from falling vegetation.

6.3 Rail Vehicle Maintenance & Operations

6.3.1 Heat Waves

6.3.1.1 Short-Term Strategies

As with its bus fleet, MARTA could consider establishing temperature thresholds for more frequent inspections of the air conditioning and electrical systems on its rail vehicles during extremely hot days.

To better protect employees from the threat of heat exhaustion and heat stroke, the agency may consider evaluating its existing policies on rail maintenance worker safety during hot days and update or clarify these policies as necessary to ensure their safety. This update could include establishing temperature thresholds at which specific actions are taken to protect rail employees from heat-related illnesses.

6.3.1.2 Long-Term Strategies

Again, as with its bus fleet, the agency could update its design standards for new rail vehicles to incorporate heat-resistant materials where feasible, increased ventilation for electrical components, and more durable air conditioning systems. In addition, the air

conditioning systems on existing rail vehicles could be replaced with systems designed for longer operating cycles.

6.3.2 Flooding from More Intense Precipitation During Storms

6.3.2.1 Short-Term Strategies

As with bus storage and maintenance facilities, the agency could develop and establish a combined emergency shutdown and restart plan for all rail maintenance facilities located in flood prone areas and practice the plan with facility employees.

A specific issue that was identified in Chapter 5 during intense precipitation events was the train operator's use of emergency braking mode to come to a stop at a rail station, which damages the rail vehicle's wheels. To help resolve this issue, MARTA may investigate alternative techniques that train operators can employ to stop trains properly without enabling emergency braking mode.

6.3.2.2 Long-Term Strategies

When feasible, the agency could consider relocating rail maintenance facilities away from flood prone areas. If relocation is not feasible, the agency may either harden these facilities against the threat of flooding or abandon them.

6.3.3 Droughts

6.3.3.1 Short-Term Strategies

As with its bus fleet, the agency could establish a rail vehicle-washing plan for different levels of drought severity.

6.3.3.2 Long-Term Strategies

Again, similar to its bus facilities, the agency could consider replacing all rail vehicle-washing facilities with more water-efficient systems that use low-flow heads and

water reclamation. In addition, these systems could utilize non-potable sources of water for washing, such as local groundwater or rain barrels.

The agency may also investigate if there are certain materials or coverings that could be installed or applied to rail vehicles that reduce the frequency of washing, regardless of drought condition.

6.3.4 Wider Temperature Variations

6.3.4.1 Short-Term Strategies

While MARTA's rail vehicles are not as vulnerable to extremely cold temperatures as they are extremely hot temperatures, the agency could investigate and identify materials and components that are the most impacted by wider temperatures ranges over time.

6.3.4.2 Long-Term Strategies

The findings of the agency's investigation may be incorporated into updated design standards that specify materials and components that can better withstand greater temperature ranges.

6.3.5 More Frequent High-Wind Events

6.3.5.1 Short-Term Strategies

Again, as with its bus fleet, MARTA could establish wind velocity thresholds at which service is slowed or suspended on elevated track structures and stations.

6.3.5.2 Long-Term Strategies

Eventually, the agency could institutionalize modified operating procedures for high wind conditions.

6.4 Track & Structures

6.4.1 Heat Waves

6.4.1.1 Short-Term Strategies

While MARTA already utilizes standard operating procedures for the inspection and maintenance of its track, these procedures could be updated to include temperature thresholds for conducting more frequent and thorough inspections during extremely hot days. In addition, standard operating procedures regarding the inspection, maintenance, and replacement of rail and track elements during extreme weather conditions could be re-evaluated and ultimately unified into one plan and document.

6.4.1.2 Long-Term Strategies

If issues with rail and track elements due to extreme heat continue to increase over time, the agency may consider replacing track elements and rail with more heat-resistant materials and/or expansion joints.

6.4.2 Flooding from More Intense Precipitation During Storms

6.4.2.1 Short-Term Strategies

Since most track flooding issues have been the result of clogged drainage systems, the agency may conduct more frequent inspections of drains and pipes near tunnel entrances (specifically the interline connector between Garnett and Five Points stations) and on aerial structures to check for clogging.

6.4.2.2 Long-Term Strategies

If issues with flooded tracks near tunnel entrances and on aerial structures persist due to overwhelmed drainage systems, the agency could consider increasing the drainage capacity in these areas.

6.4.3 Droughts

6.4.3.1 Short-Term Strategies

While drought does not directly affect MARTA's track and structures, the vegetation within and near the rail right of way can pose a fire hazard. Therefore, the agency could cut back or remove vegetation that may pose a fire hazard within its own right of way as well as conduct outreach efforts with stakeholders located near the right of way to remove or cut back vegetation that poses a hazard but is not within MARTA's jurisdiction to remove.

6.4.3.2 Long-Term Strategies

Ultimately, the agency may consider establishing a plan for regularly identifying and removing hazardous vegetation within and near the rail right of way that poses a fire hazard with coordination from local stakeholders who may be affected.

6.4.4 Wider Temperature Variations

6.4.4.1 Short-Term Strategies

Because rail expands and contracts with fluctuating temperatures, MARTA could identify areas within the rail network that are most vulnerable to large temperature fluctuations.

6.4.4.2 Long-Term Strategies

If issues with the rail due to temperature fluctuations persist over time, the agency could consider installing systems such as expansion joints to allow the rail to expand and contract without compromising the integrity of the rail or the allowable system speed on the rail.

6.4.5 More Frequent High-Wind Events

6.4.5.1 Short-Term Strategies

As with drought conditions, the agency may cut back or remove vegetation that may pose a potential falling or debris hazard within its own right of way as well as coordinate with stakeholders located near the right of way to remove or cut back vegetation that poses a hazard but is not within MARTA's jurisdiction to remove.

The King Memorial rail station is the highest elevated station in the MARTA rail network and was damaged by the tornado that occurred in downtown Atlanta in 2008. Therefore, the agency could establish wind speed thresholds for reducing and suspending service to King Memorial station.

6.4.5.2 Long-Term Strategies

Ultimately, the agency could establish a plan for regularly identifying and removing vegetation within and near the rail right of way that poses a falling or debris hazard with coordination from local stakeholders who may be affected.

While lowering the elevation of the King Memorial station is uneconomical, its structure may be retrofitted to withstand higher wind speeds before damage occurs.

6.5 Civil Engineering & Design

6.5.1 Heat Waves

6.5.1.1 Short-Term Strategies

Because the civil engineering and design department is primarily responsible for overseeing updates to the MARTA's design standards, it should continue to monitor how extremely hot days and heat waves affect facilities, materials, and assets.

6.5.1.2 Long-Term Strategies

While specific departments (such as bus or rail vehicle maintenance) may express the need to update design standards for certain assets, it is within the purview of the civil engineering and design department to respond to those needs and provide updated design standards to those departments that incorporate heat-resistant materials where feasible.

6.5.2 Flooding from More Intense Precipitation During Storms

6.5.2.1 Short-Term Strategies

In order to reduce the risk of overwhelming MARTA's existing drainage infrastructure, the agency may coordinate with development stakeholders near the right of way to reduce or eliminate additional water runoff into the right of way. In addition, the agency could establish policies and procedures for regularly inspecting and (if necessary) clearing drains and pipes.

While most of MARTA's infrastructure is located out of existing floodplains, the agency should be aware of updates to FEMA's floodplain maps.

6.5.2.2 Long-Term Strategies

If the risk of flooding continues to rise, the agency could incorporate higher flood design standards for facilities, pipes, and drains. The agency may also incorporate low-impact developments (e.g. rain gardens, bioswales, etc.) into the design of new and existing facilities to reduce runoff into the drainage system.

6.5.3 Droughts

6.5.3.1 Long-Term Strategies

If the agency's investigation of subsurface conditions during prolonged drought raises concerns about the integrity of subsurface structures over their lifetime, the agency could modify its design standards for these structures to account for these concerns.

If more frequent droughts result in the need to reduce water usage, the agency may consider incorporating water-saving systems (e.g. low-flow faucets and toilets) and non-potable water usage into its design standards for new facilities and retrofit existing facilities with these systems where feasible.

6.5.4 Wider Temperature Variations

6.5.4.1 Short-Term Strategies

Similar to the concerns about extremely hot days and heat waves, the agency could identify and monitor structures, materials, and equipment that are vulnerable to large temperature fluctuations.

6.5.4.2 Long-Term Strategies

If the agency determines that certain types of materials are more susceptible to large temperature fluctuations, it could update the design standards related to those materials to incorporate new materials that can withstand a wider range of temperatures.

6.5.5 More Frequent High-Wind Events

6.5.5.1 Short-Term Strategies

The agency could identify areas in the system that are the most vulnerable to high wind velocities and seek to protect these areas to ensure the safe operation of the system.

6.5.5.2 Long-Term Strategies

In future updates to infrastructure design standards, the agency could account for greater wind velocities.

6.6 Capital Facilities

6.6.1 Heat Waves

6.6.1.1 Short-Term Strategies

While it is within the purview of the civil engineering and design department to be generally responsible for monitoring how extreme heat and heat waves affect MARTA's facilities, materials, and assets, it is also within the purview of the capital facilities department to conduct a detailed analysis of the effect of heat waves on major capital infrastructure.

6.6.1.2 Long-Term Strategies

When major capital infrastructure is due for replacement, the agency may utilize updated design standards for new infrastructure that incorporate heat-resistant materials where feasible.

6.6.2 Flooding from More Intense Precipitation During Storms

6.6.2.1 Short-Term Strategies

Within the rail right of way, MARTA may identify areas that have steep slopes and identify strategies for preventing mudslides onto the tracks and erosion of the rail foundation during heavy precipitation events.

Based on an analysis of existing floodplain maps and the identification of other flood prone areas, the agency could harden its most vulnerable capital facilities against the threat of flooding.

6.6.2.2 Long-Term Strategies

If the risk of flooding continues to rise from groundwater seepage and near tunnel entrances during intense precipitation, the agency may increase the pumping capacity at underground stations in these areas.

If the hardening of the capital facilities most vulnerable to flooding is uneconomical over time, the agency could consider abandoning these facilities and/or

relocating to new facilities with designs that incorporate more stringent flood design standards. In addition, up-to-date floodplain maps may be considered when siting new major capital facilities.

After identifying areas with steep slopes and strategies for addressing mudslides and erosion, the agency could implement the strategies in those areas.

To improve customer comfort at bus stops during intense precipitation events, the agency may evaluate the feasibility of providing bus shelters at stops that are currently without a shelter.

6.6.3 Droughts

6.6.3.1 Short-Term Strategies

To reduce water usage during drought conditions, the agency could post information in relevant areas such as bathrooms on how to conserve water.

6.6.3.2 Long-Term Strategies

If informational efforts are not sufficient to reduce water usage over time during droughts, the agency could require that new and rehabilitated facilities utilize systems such as low-flow faucets, water fountains, and cleaning apparatuses that reduce water usage.

6.6.4 Wider Temperature Variations

6.6.4.1 Short-Term Strategies

To better understand the size of its resource consumption footprint, MARTA could establish and measure its energy and water use.

6.6.4.2 Long-Term Strategies

In order to reduce the size of its consumption footprint, the agency may seek to retrofit existing capital facilities to meet “green” building design standards (e.g. LEED), while also requiring that new facilities be certified to a certain level of the same standard (e.g. LEED Silver).

6.6.5 More Frequent High-Wind Events

6.6.5.1 Short-Term Strategies

In order to reduce the risk of significant service disruption from failure or damage of MARTA’s primary communication antennas, the agency could prepare an alternative communication plan and distribute back-up communication equipment to the most critical agency staff and operators.

6.6.5.2 Long-Term Strategies

The agency may consider installing a secondary communication system that can be activated in the event of primary communication disruption or failure so that the disruption to service is minimal.

6.7 Architecture

6.7.1 Heat Waves

6.7.1.1 Short-Term Strategies

In order to improve customer comfort and safety during extremely hot days or heat waves, MARTA could conduct an assessment of available shade at and approaching bus stops and rail stations. Based on this assessment, the agency could develop a plan for improving shade conditions at the most vulnerable locations first. In addition, the agency could evaluate different methods to increase the natural airflow in stations to aid in keeping customers cool.

6.7.1.2 Long-Term Strategies

Once the agency has improved shade conditions at the most vulnerable stops and stations, it may continue to increase the level of shading at and around other bus stops and rail stations, especially at bus stops that do not have shelters.

In addition, the agency could implement the best methods it identifies for improving natural airflow in rail stations. If, for certain stations, these methods would be unfeasible, the agency may consider installing enclosed, air-conditioned areas in those rail stations that can be made available during extremely hot days.

6.7.2 Flooding from More Intense Precipitation During Storms

6.7.2.1 Short-Term Strategies

As with the civil engineering and design department, the agency could develop and implement a coordination effort with local communities and governments to reduce runoff from both existing and future developments near MARTA's right of way.

Because many of the original roofs in MARTA rail stations were designed with no pitch and have exceeded their expected useful life, the agency could develop a roof replacement prioritization plan.

6.7.2.2 Long-Term Strategies

When the roof prioritization plan is implemented, the agency could replace the original roofs with more durable, weather-resistant material and with a pitch to allow water to drain properly.

To further reduce water runoff into the drainage system, the agency may consider installing low-impact developments (e.g. rain gardens, bioswales) at and around bus stops and rail stations. In addition, the roof replacement prioritization plan may include the installation of low-impact developments to capture and filter rainwater runoff.

6.7.3 Droughts

6.7.3.1 Short-Term Strategies

Even though MARTA has planted more local, drought-resistant vegetation near its stations, the plants have struggled to grow not only because of prolonged drought conditions but also because of customer abuse. Therefore, the agency could try different methods to better protect newly installed vegetation from this abuse.

6.7.3.2 Long-Term Strategies

As mentioned previously, the roof replacement prioritization plan may consider utilizing low-impact developments to capture and filter the rainwater runoff. However, if the rainwater runoff of a roof exceeds the capacity of the low-impact developments serving it, the agency may also develop a plan to capture and utilize the excess rainwater to water other plants that are not part of the low-impact developments.

6.7.4 Wider Temperature Variations

6.7.4.1 Short-Term Strategies

As with the original roofs at its rail stations, the agency could develop a plan to prioritize the replacement of all original station floor areas that have exceeded their expected useful life. The plan should seek to replace platforms in outdoor stations first, since these are generally more exposed to the elements than those in underground stations. As part of the development of this plan, the agency could evaluate new materials and installation techniques for making the platforms more resistant to damage from freeze-thaw cycles.

6.7.4.2 Long-Term Strategies

When the station platform replacement plan is implemented, the agency may replace the most vulnerable station platforms with the materials and installation techniques that were identified to be the most resistant to damage from freeze-thaw cycles.

6.7.5 More Frequent High-Wind Events

6.7.5.1 Short-Term Strategies

To help reduce the risk of vegetation becoming a falling or debris hazard around rail stations and the rail right of way, the agency may identify landscape designs (whether natural or manmade) that could reduce or better withstand high wind velocities.

6.7.5.2 Long-Term Strategies

In addition to the landscape design around rail stations and the rail right of way, the agency may consider incorporating aesthetic elements in these areas that can reduce or divert high wind velocities.

6.8 General Adaptation Strategies

In addition to the strategies discussed above, there are several general climate adaptation strategies that could address multiple climate stressors or departments.

6.8.1 Establishing a Policy & Developing a Plan

One of the most important efforts that MARTA could undertake is the development and establishment of an agency-wide policy on addressing climate change. This policy should clearly state how addressing climate change falls under MARTA's core responsibilities to provide safe, reliable, and cost effective transit service within its service area. It should also outline a vision for utilizing climate adaptation and mitigation strategies to ensure these responsibilities continue to be met. A subsequent and related strategy after such a policy has been established could be the development and

implementation of a climate change adaptation and mitigation plan. This plan could utilize the adaptation strategies provided in this chapter along with input from key decision makers at the agency to establish a set of goals (based on the vision established in the agency's climate change policy) and a timeline for achieving them. The plan should be updated at regular intervals to measure progress towards the original goals, revise the goals as necessary, and identify additional strategies for implementation.

6.8.2 Emergency Evacuation, Operation, & Recovery

There are three general adaptation strategies that relate to MARTA's operations and facilities before, during, and after extreme weather events. First, MARTA could coordinate with local weather services to identify extreme weather events within the service area in real time, so that emergency crews can be prepared and dispatched promptly to address any issues in the affected area. Second, MARTA could install sufficient generator capacity to entirely power its bus maintenance facilities and their equipment during power outages or other emergency situations. Finally, MARTA may develop a system accessibility plan to define what level of service can be provided during or after extreme weather events as well as how the access to that service will be maintained during or after the event (e.g. snow/ice removal from station entrances and walkways).

6.8.3 Utilizing the "Crowd"

An innovative strategy that could improve MARTA's ability to identify and respond to issues with its infrastructure, operations, and assets would be to allow passengers to utilize social media platforms such as Twitter to crowd-source the identification of issues to key agency personnel. A potential advantage to this strategy is the reduction in inspection costs for non-critical assets and infrastructure, while providing enhanced and more frequent inspection of critical assets and infrastructure. A potential

disadvantage to this strategy is the amount of time required to filter “false positive” issues from actual issues in the system, which is due to the fact that most passengers are not trained professional inspectors.

CHAPTER 7

ADDRESSING CLIMATE CHANGE ADAPTATION THROUGH MARTA’S ASSET MANAGEMENT PROGRAM

Most of the material in this chapter is reported from the following document: Task 3: Draft Technical Memorandum – Addressing Climate Changes and Hazards using MARTA’s Asset Management Program [9].

7.1 Introduction

Transit has multiple benefits, moving people safely, reliably and affordably in various metropolitan areas, cities and towns nationwide. Transit supports economic development, improves the societal quality of life, provides mobility to vulnerable populations and helps to protect and sustain our environment by offering alternative mode choices to highway travel [21]. Ultimately, transit agencies that can proactively deliver effective climate risk management stand to protect these benefits for their customers and the broader societies they serve, and preserve their ability to continue to build and expand upon the significant cumulative investments made in their transit systems thus far. At the same time, agencies should be cautious and wise in how they expend limited funds on climate-related issues in the face of other critical priorities such as SGR backlogs. This is where an asset management platform can be very useful and effective in providing the appropriate decision support. This chapter discusses the development, current structure, and maturity of MARTA’s asset management program as well as identifies a framework for addressing climate adaptation through the program.

7.2 MARTA’s Asset Management Program

7.2.1 History of Development

Since the mid-1970s, MARTA has been involved in construction and expansion of the transit system for Atlanta. A combined bus and rail service was launched in 1979 with assistance from the FTA. In the 1990s, MARTA implemented a Maintenance Management Information System platform responding to the need to accurately monitor and prioritize assets. The MMIS provided asset data access to operations and maintenance decision makers resulting in more cost-efficient decisions, and building the foundation for MARTA's current SGR program. In 2006, MARTA leadership saw the need to better utilize asset management data in developing long-term capital planning needs prompting the agency to re-evaluate their Asset Management Program including asset breakdown structure, priority and condition codes, and replacement values. MARTA initiated a business transformation project with the goal of linking financial, MMIS and resource allocation systems together in a single Enterprise Asset Management system that would enable the use of asset management data in the development of long-term capital planning needs. The EAM (which utilized the AssetWorks/FASuite platform) integrated asset information at MARTA into a single platform, a tool that could be used for agency-wide asset management programming with implementation of the right processes and support tools across the agency. In 2009, MARTA joined the FTA's State of Good Repair Workgroup and attended the inaugural SGR Roundtable, which was followed up with accelerated efforts to modernize the existing asset management program, based on a full understanding of the extent of the national asset backlog issue [21].

In 2010, MARTA initiated an agency-wide condition assessment with an aggressive approach to improving, cataloging and prioritizing asset data. This effort provided the basis to implement the following initiatives [21]: identification of a project management team to oversee execution of MARTA's **Asset Management Plan**; introduction of **periodic assessments** driven by condition and operational priority as well as useful life; update of the **30-year capital needs forecast** including the backlog, using

lifecycle data, condition and priority codes; initiated the development of a new **capital planning module** in partnership with agency's enterprise asset management partner AssetWorks/Trapeze, which will develop projects directly from the asset database; initiated implementation of **Expert Choice decision-making software** to prioritize projects for portfolio optimization, which selects the best-value projects when the capital budget is constrained; and initiated re-engineering of project delivery and controls to increase the success of delivering Capital Improvement Program on time and within budget. Successful implementation and integration of these initiatives is expected to provide the foundation and tools for an asset management program that delivers a safe, high-performance and sustainable system.

7.2.2 Structure and Functions of MARTA's Asset Management System

MARTA's TAM program is composed of two primary systems that are linked by the information they provide to one another. MARTA utilizes EAM system software. The EAM is the central platform for all asset management data at MARTA. The system stores basic inventory information (such as ID, status, mileage, and location) for all of MARTA's physical assets, as well as condition assessment data (if available). The EAM system tracks the asset (and all of its subcomponents) over its life cycle – from procurement to salvage - since it is designed to create, process, and close maintenance work orders for MARTA's assets. While several systems consider only the age of an asset in project prioritization for repair or replacement, MARTA also factors in asset condition and criticality (e.g., life criticality, safety criticality, and operation criticality).

To ensure that the asset data is current, MARTA periodically conducts condition assessments. MARTA conducted its first asset condition assessment in 2000 and is currently completing another condition assessment. Because of the high cost and time that would be needed to inspect and determine the condition of every asset in the MARTA system (over 53,000 total), MARTA decided to adopt a sampling approach to

determine the overall condition of its assets. A statistically significant sample size was determined for each asset category and assets within the category were inspected at random and assigned a condition rating ranging from 1 (failed) to 5 (excellent), based on the FTA's guidelines for condition ratings. In addition, a minimum of 30 assets were inspected for each asset category, and all assets for certain categories (e.g. life-safety critical) were inspected. Currently, the EAM is only able to analyze and prioritize assets within a single asset group (e.g., buses), however, this issue is expected to be corrected within the next year through implementation of a new capital planning module.

The second system within MARTA's TAM program addresses the Capital Improvement Program. This system uses information generated by the EAM system to develop a list of priority projects to be completed over the next several years based on the agency's most critical needs and priorities. This software-based decision tool (developed by Expert Choice) generates an optimal portfolio of projects to implement over the time frame of the CIP based on agency criteria, funding constraints, and agency needs. While the current EAM system can only prioritize assets within a single asset group, the new Capital Planning Module will be able to prioritize assets across multiple asset groups. Currently, candidate CIP projects are created and developed by MARTA's individual departments, through project sponsors and champions, and then further culled by the CIP's Project Delivery/Project Controls process. The new Capital Planning Module will allow the EAM to automatically generate portfolios of projects from the data stored within the system for consideration in the CIP.

Figure 7 depicts MARTA's Asset Management program.

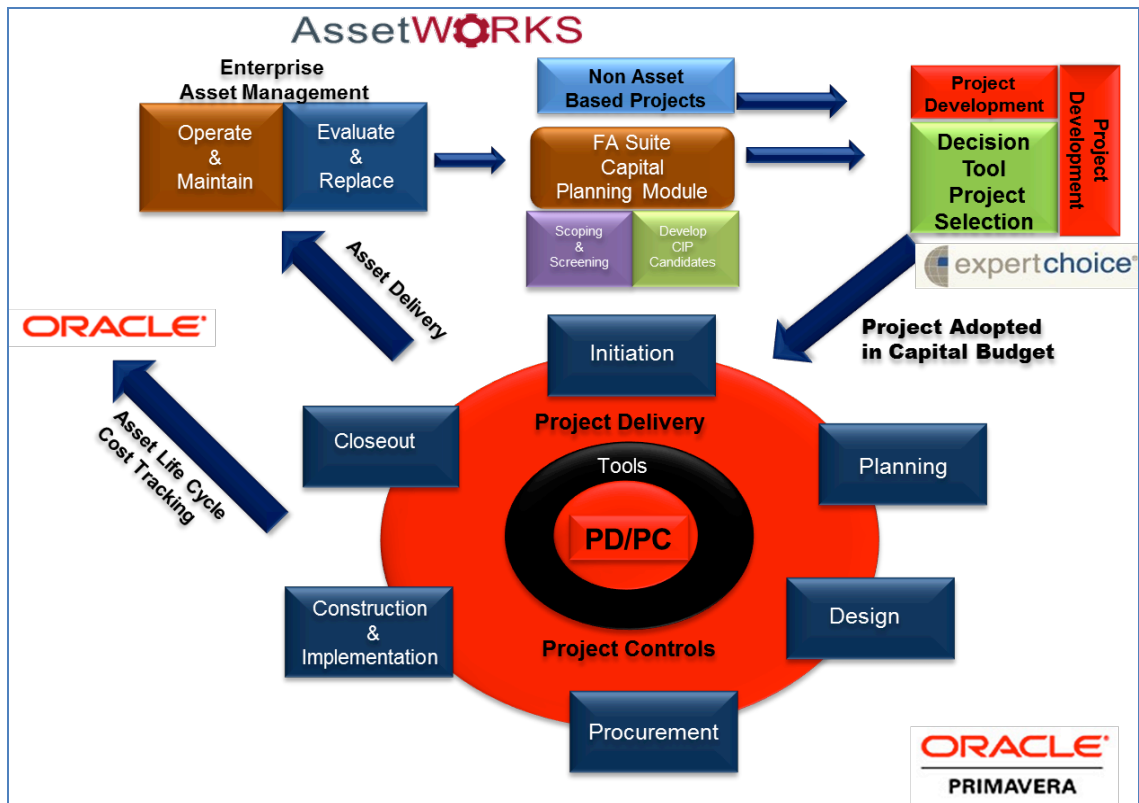


Figure 7. MARTA's Asset Management Program

7.2.3 Level of Maturity

It is important that any transit agency developing its own asset management program should periodically assess the program's level of maturity both against an original baseline (if one was established at the beginning of the program's implementation) and against any goals or targets that have been established for the program. The FTA's *Asset Management Guide*, while currently in draft form, contains a section that discusses how a transit agency can assess the level of maturity of its asset management program. The guide currently defines five levels of maturity, with a brief explanation of each level. The level of maturity ranges from establishing a clear asset management vision (Level 1) to utilizing analytical tools to optimize funding for various asset classes (Level 5). However, the guide notes that agencies may have asset management activities that cover the entire range of maturity, but may have put more

effort into some aspects than others [12]. Based on the guidance within the Asset Management Guide, the current structure and development of MARTA's asset management program is nearing a maturity level of four. This is because – as mentioned previously – MARTA has developed a robust and comprehensive asset inventory, conducted a series of condition assessments using statistically significant sampling, and developed a platform and process for objectively compiling capital project portfolios based on agency goals. In addition, MARTA is in the process of developing and integrating both a capital planning module and decision-making tool to further enhance the ability of decision makers to identify and prioritize the capital needs of the agency.

While MARTA has one of the most mature asset management programs in the country, there are still several areas for improvement. First, while the agency is planning to conduct more periodic condition assessments, these assessments could be scheduled to occur at regular intervals and be comprehensive (i.e. the condition of all assets should be known). Second, the agency could establish clear and measurable asset management targets to be compared against a baseline condition of maturity. This maturity baseline, while generally assessed in this chapter to be “Level 4”, could be more precisely defined by utilizing the *Transit Asset Management Maturity Agency Self-Assessment* contained within the appendix of the Asset Management Guide. In addition to assessing an overall maturity score for the program, the self-assessment also provides “scores” for the program's enterprise-level and asset-level frameworks [12]. These scores would allow to agency to easily identify areas for improvement. Finally, the agency could modify the capital planning module and decision-making tool to optimize funding across and within asset categories.

7.3 Addressing Climate Adaptation through MARTA's TAM Program

Both because transit agencies have other critical priorities (e.g. service performance) and there is appreciable uncertainty associated with climate change

predictions, transit agencies are likely to consider climate change risks in the context of existing critical priorities -- particularly for climate hazards with non-catastrophic and lower-impact failures, and where these affect non-critical infrastructure. On the other hand, agencies may consider pursuing alternative sources of funding to address hazards associated with catastrophic and high-impact failures, and especially where these affect critical infrastructure.

7.3.1 State of Good Repair as a Starting Point

A systematic approach to addressing climate hazards in transit agencies is likely to be developed within the context of ongoing systematic decision making at transit agencies on the state of good repair of their assets -- indicating that several transit agencies may begin to consider climate change in the context of their asset management programs and practices. The *Rail Modernization Study* assessed capital investment needs for the nation's seven largest transit operators -- the CTA, MBTA, New York MTA, NJ TRANSIT, BART, SEPTA, and WMATA-- agencies that collectively account for 80% of annual passenger boardings, 51% of track miles, 57% of passenger stations and 74% of fleet vehicles. The study showed that \$50 billion (2008 dollars) would be needed to replace all assets exceeding their useful life, and rehabilitate all stations, with an additional \$5.9 billion (2008 dollars) per year to maintain the assets in good condition beyond that. The study also found that all seven transit agencies had asset management processes in place at different levels of maturity [5].

The Rail Modernization Study has at least three implications in the context of climate change impacts to public transit agencies, systems and services: (i) a significant inventory of transit capital is potentially vulnerable to climate changes or hazards nationwide; (ii) climate change considerations will largely be made in the context of SGR and budgetary considerations, in a competitive and/or complimentary manner; and (iii) asset management programs are a logical platform to consider systematic climate change

risks for entire public transit systems. From the catastrophic and non-catastrophic nature of the impacts of climate hazards, as well as their relative impact levels, appropriate approaches to climate changes and hazards may be either progressive and systematic or aggressive and urgent as depicted in Figure 8. While agencies may take a more progressive approach to addressing lower-impact scenarios, they may find it ultimately more beneficial to their customers and the societies they serve to take a more aggressive stance toward identifying and addressing higher-impact scenarios. The decision-making approaches and funding considerations may be different in these different cases, and the relative criticality of assets will also be important in prioritizing assets for climate-change retrofits.



Figure 8. Severity-Impact Categorization of Climate Events on Infrastructure and Society

7.3.2 A Framework for MARTA

MARTA’s overarching goals involve the provision of safe, reliable, cost-effective, and high quality transit for their customers as captured by their mission statement: “The mission of the Metropolitan Atlanta Rapid Transit Authority (MARTA) is to strengthen communities, advance economic competitiveness, and respect the environment by providing a safe and customer-focused regional transit system” [22]. A

systematic approach to considering climate change impacts on transit system services and infrastructure should identify the range of ways in which current and anticipated future climate hazards in the region could affect MARTA's ability to achieve their mission or objectives, namely, the provision of *safe, reliable and cost-effective transit*. From this standpoint would emerge a hierarchy of efforts that would *prioritize mission critical* (e.g., life critical, safety critical, operation critical) *assets and services* over non-mission-critical ones. Within both mission-critical and non-mission-critical assets and services, priorities would be accorded based on the anticipated *level of severity* and *extent of impact* of various hazard scenarios (see Figure 8), as well as the relative chance of those scenarios occurring. Finally, all of these decision criteria should be considered within the *constraint of the existing budget*. However, in the case where *extreme scenarios* were identified that could significantly jeopardize the viability of the region and there was a reasonable chance that these scenarios would occur over the planning timeframe, more accelerated approaches involving MARTA's leadership may be considered to identify alternative sources of financing to take more aggressive proactive and preemptive actions to address these scenarios. Given that SGR considerations are on the top of the list of MARTA's critical priorities, any considerations on climate change risks would be occur within the context of SGR priorities, existing budgetary constraints and other critical priorities and constraints.

This decision framework could be considered as a benefit-risk framework, where climate factors are incorporated within the context of the agency's existing asset management framework. In this framework, climate factors would be considered as part of the CIP. The relative priorities given to climate factors would depend on the factors discussed above, namely, the mission criticality of the asset under consideration, the relative levels of severity, the relative extent of impact of the climate hazards under consideration, and the relative likelihood of their occurrence. This *risk management framework* could be considered as one that could be incorporated into the existing asset

management platform either *aggressively* or *progressively* depending on the urgency posed by the climate factors under consideration. In practice, implementation is more likely to be adaptive (i.e. iterative) as more information becomes available on climate hazards; climate change forecasts for different climate factors currently have various degrees of uncertainty associated with them – appreciable in most cases. An *adaptive management framework*, used for resource management under uncertainty, would be a useful construct in which to think about adapting to climate change as more information becomes available on climate hazards. Adaptive management is a structured, iterative process of decision making in the face of uncertainty that seeks to reduce uncertainty over time through system monitoring and additional data collection reduce uncertainty. Adaptive management is increasingly being viewed as an appropriate framework for addressing climate change issues [23]. All of this implies that a formalized approach to addressing climate change considerations would be helpful in transit agencies as it would formalize the process within the existing decision support systems and processes, allowing for periodic updates to reduce uncertainty as more climate change information becomes available. For example, a climate-sensitive Asset Management Plan would include considerations of how current and foreseeable climate conditions can be expected to influence the agency’s ability to achieve their goals. Falling out from that would be actions to enhance the agency’s existing decision support capabilities to address these climate risks in a way that minimizes their ability to obstruct the agency’s ability to achieve their goals -- in the most cost effective manner. This way, capital improvement, operations and maintenance, rehabilitation and renewal decisions would all take into consideration the appropriate climate risks that have a bearing on the agency’s decision outcomes. With this overarching framework, **Table 3** offers a range of ways in which MARTA’s Asset Management program may be used to address climate change issues proactively.

Table 3. Addressing Climate Changes and Hazards through MARTA's TAM Program

Organizational Element	Climate-Sensitive Retrofit	Notes
Policy, Goals and Objectives	Develop climate change policy with supporting goals and objectives	The process of developing a formal climate change policy will assist agencies in developing their knowledge on the real risks of climate change to their operations and assets.
Organizational Factors		
Staffing	Assess the value of staff time to address climate change issues on a periodic/consistent basis.	Agencies that address climate issues proactively will be better informed to develop climate risk management capabilities proactively.
Asset Management		
Asset Management Plan	Asset Management Plan update including the effects of climate change and how they can be addressed	Agencies that take the initiative to develop climate-sensitive AMPs will be better positioned to take leadership in in addressing mission-critical, high-risk, high-impact climate scenarios and events. Periodic AMP updates offer a formalized opportunity to update climate change considerations as more data becomes available.
Asset Management System Database (Data Collection)	Expand organizational capabilities to include expert or staff time for climate assessment and action plan with respect to agency assets and services.	E.g., Condition assessment can be conducted in collaboration with expert to integrate climate forecasts for service area and assess vulnerability of system to anticipated climate risks.
Enterprise Asset Management system (Analysis of Alternatives including Tradeoffs)	Develop a code for climate-sensitivity of assets and input information first for mission-critical assets and then for other assets. While several transit agencies consider the age of an	The EAM system comes with the capability for adding fields that can designate particular asset groups, types or components as being

	asset for repair and replacement decisions, MARTA considers asset condition and criticality (i.e., life safety criticality, operation criticality, etc.) as well. A climate sensitivity code can be developed with respect to the level of severity, extent of impact and probability of climate-related failure of an asset.	vulnerable to different climate stressors, to different degrees.
Expert Choice Decision-Making Software (Resource Allocation Decision Making)	The Expert Choice decision-making tool will assist the CIP committee in making decisions based on a set of agency goals and objectives that can be accorded different levels of importance based on the agency's changing priorities. A climate-related goal can be included in the current goals capturing MARTA's desire to make assets and operations more resilient to the effects of climate change. The relative importance of climate considerations can be managed by the weight given to climate factors in the model.	Infrastructure resilience to climate hazards and disasters is a desirable attribute for a transit agency in this modern climate era. However, the relatively high levels of uncertainty associated with predicting climate changes makes an adaptive management framework desirable; one that can respond to changes and new information revealed with better data over time. The weighting approach used in the decision-making software is a good platform on which to implement such an adaptive approach
Design Standards	Engineering design standards may be developed to address changing climate, e.g., higher frequency and intensity of storms.	
Disaster Management and Recovery		
Disaster Recovery Plan (DRP)	Where it makes sense, develop DRP that outlines MARTA's role in different realistic disaster scenarios.	Agencies that develop DRPs proactively will be better prepared for quick and effective recovery in the aftermath of a disaster.
Post-Disaster Smart Rebuilding	Transit agencies that experience disasters such as the 2012 Super Storm will be better prepared to rebuild smart, relative to climate risks, if they have spent some time thinking through the	Post-Disaster rebuilding, while all disasters remain undesirable, may be viewed as an opportunity to rebuild and renew infrastructure in smarter ways to improve

	potential impacts of climate risks on their operations and services and identified how they can modify their actions to achieve a higher level of resilience in their transit facilities and operations.	resilience in the face of changing climate patterns.
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CHAPTER 8

A GENERAL FRAMEWORK FOR OTHER TRANSIT AGENCIES

While this thesis has primarily focused on how climate change adaptation can be addressed through MARTA's transit asset management program specifically, this chapter discusses a general framework that transit agencies can use.

8.1 Transit Asset Management

Because transit agencies are ultimately responsible for providing safe, reliable, cost-effective service to their customers by properly operating, maintaining, rehabilitating, and replacing assets and because these assets and activities are most likely to be affected by changes in the environment, a basic transit asset management program provides a foundation through which climate change and climate adaptation can be addressed. At minimum, a transit asset management program should have several key components. First, there should be a policy that establishes a vision for the program in the context of the agency's mission or responsibilities. From this vision, the program should have established goals for asset performance and performance measures that the program can utilize to monitor its progress towards accomplishing these goals. Second, a transit asset management program should have an inventory of the agency's assets that contains at least basic information about each asset, which includes both inventory data such as the asset type, location, procurement date and attribute data such as maintenance/rehabilitation history, condition, replacement cost, and expected remaining useful life. Third, utilizing the asset inventory data, the program should be able to analyze the impact of different funding scenarios on asset conditions over time. Fourth, the program should have a process for prioritizing the capital needs of the agency based on given funding scenarios and the goals for the program outlined in the policy. Finally, the performance of the program towards meeting its goals should be monitored regularly

utilizing the performance measures established in the policy. The program should also be updated regularly to establish new goals as others are achieved, refine performance measures as better techniques become available, and shift priorities as agency objectives change.

8.1.1 The FTA's Asset Management Guide

If a transit agency has not yet implemented its own transit asset management program or is seeking to improve the capabilities of its existing program, the FTA's Asset Management Guide will soon provide a wealth of information to assist agencies in either of these situations.

The guide will provide assistance in four key areas. First, the guide introduces the concept of transit asset management. This includes defining asset management in the context of the transit industry, outlining the benefits of asset management to an agency, describing how asset management can address different types of challenges faced by agencies, and providing a general framework for agencies to build off of. Specifically, the guide's discussion of the general asset management framework includes the introduction of the three business processes necessary to the success of the program: vision and direction, lifecycle management, and cross-asset planning and management. Second, the guide discusses each of these three business processes in detail, which includes a discussion of the roles within each process, their importance to the overall framework, and examples of "best practices" in the industry. Third, the guide discusses the components of the information system that supports the asset management framework, some components of which most transit agencies already have in some form or another. This includes components such as asset inventory, asset condition, maintenance management, scenario analysis, and financial and accounting management. The information system that results from the tight integration of these components is referred to as an Enterprise Asset Management (EAM) system. Finally, the guide provides a four-

step approach to implementing an asset management program. The first step involves preparing for implementation by assessing the agency's awareness to asset management, identifying asset management "enablers", and establishing leadership and responsibility for the implementation process. The second step involves assessing the maturity of the agency's asset management program by determining and communicating the current baseline of the program as well as determining the agency's target for the maturity of the program. The third step involves developing an asset management implementation plan by establishing the business case for asset management, deciding which implementation path to take, and outlining the key activities to be undertaken and which stakeholders have responsibility for those actions. The final step involves implementing the asset management program, which includes developing a communications strategy and determining an information systems strategy [12].

8.2 A Framework for Addressing Climate Change Adaptation

Once an agency has begun the process of developing and implementing its own asset management program or has developed a plan for improving the capabilities of its existing program, there are several steps that should be taken to address climate change adaptation through the program. These steps are similar to the components needed in a basic transit asset management program.

The first step in addressing climate adaptation through asset management is the establishment of an agency-wide policy on climate change. This policy should explain how addressing climate change specifically relates to the ability of the agency to achieve its mission or objectives. Based on the responsibilities of the agency, the policy should establish a vision for how the agency should address the impacts of climate change, which should include the development of an adaptation plan. From this vision, a set of goals should be established, as well as performance measures by which the initiative's progress can be monitored. Finally, while the policy should concern the entire agency, the

effects of climate change will have the greatest impact on an agency's assets and their maintenance and operation. Therefore, the policy should designate the asset management program as having primary responsibility for addressing climate change adaptation for the agency.

The second step in addressing climate adaptation is conducting a climate change vulnerability assessment. This involves using the latest climate data, climate models, and downscaling techniques to identify climate hazards that are expected to occur and/or intensify in the future within the agency's service area. The agency should then analyze the likelihood of occurrence and potential extent of impact to determine the agency's potential risk for each climate hazard identified. The extent of a hazard's impact is estimated by the vulnerability of different asset groups and operations to the hazard, which is usually based on the knowledge and experiences of agency staff.

The third step in addressing climate adaptation is identifying all potential climate adaptation strategies that could be used to address the results of the climate vulnerability assessment. These adaptation strategies could address specific assets, operations, and climate hazards or be applicable to multiple issues and be implemented soon or over a long period of time.

Once all potential adaptation strategies have been identified, the fourth step is to develop and implement a climate adaptation plan. The plan should establish a decision framework that prioritizes the implementation of a proposed climate adaptation strategy in the transit asset management program based on the likelihood of occurrence for the climate hazard being addressed, the extent of the climate hazard's impact on the asset and its operation (and ultimately the impact on the agency as a whole), the criticality of the asset under consideration to achieving the agency's mission or objectives, and budgetary constraints. The time horizon of the adaptation plan should be the same as the agency's capital improvement program so that adaptation strategies can be tightly integrated into planned asset maintenance, rehabilitation, and replacement activities.

The final step in addressing climate adaptation is to develop a process for regularly updating the framework as the goals are achieved. Updates to the framework could also result from improved climate data and modeling techniques, changes to the vulnerability of the network due to prior adaptation efforts, shifting agency goals, and significant changes in capital resources.

CHAPTER 9

CONCLUSION

This thesis has conducted a case study that investigated how MARTA can address climate change adaptation through its transit asset management program. This study utilized two downscaled climate-modeling approaches to project potential future climate scenarios within MARTA's service area in order to identify significant climate stressors. The climate stressors identified through this modeling process were used to help identify vulnerable assets, operations, and locations in the MARTA system through several interviews conducted with key MARTA staff in departments that were primarily responsible for the maintenance and operation of those assets. The results of this basic climate vulnerability assessment were used to develop a series of short-term and long-term adaptation strategies to address the vulnerabilities of the MARTA system to the climate stressors. In addition, a general framework was developed for addressing climate adaptation through MARTA's existing asset management program. Finally, based on the lessons learned in the case study, the thesis proposed a general framework that other transit agencies could utilize to address climate adaptation through their asset management programs. This chapter will synthesize the results from each part of the case study, discuss some limitations of the study's results, and propose some further research needs in this area.

9.1 Climate Stressors and MARTA's Vulnerabilities

In order to identify potential future climate stressors within the MARTA service area, the study utilized two climate-modeling approaches. The initial modeling approach was conducted by the GWRI, but only considered the highest emissions scenario (A1FI) in its projection of future climate conditions. While the results of this approach allowed the study to easily identify significant climate stressors, it was important to temper these

results by considering multiple plausible future scenarios. Therefore, the supplementary modeling approach taken by J.P. O’Har utilized a more comprehensive range of emissions scenarios: A1FI (high), A2 (mid), and B1 (low). The results of both of these modeling approaches, as well as discussions with MARTA staff, indicated an increased likelihood of higher temperatures with heat waves, more frequent below-freezing temperatures, more intense and frequent precipitation, a wider variation in temperatures, and droughts within the MARTA service area. While nearly impossible to project using existing climate models, the results of the analysis also indicated an increased likelihood of intense winds and tornado events.

Utilizing the results of the climate stressor analysis as a guide, several interviews were conducted with key MARTA personnel to understand the vulnerability of MARTA’s assets and operations to the effects of climate change. Additional interviews also sought to identify specific locations that, based on historical staff experience, would be particularly vulnerable to different climate stressors. The result of these interviews found that, in general, the MARTA system is most vulnerable to extreme heat (and heat waves) and intense precipitation (which can cause flooding). To a lesser degree, there were also vulnerabilities with respect to intense winds and tornadoes, droughts, and wider variations in temperature. The study also produced two maps showing vulnerable locations in MARTA’s bus and rail networks.

9.2 Climate Adaptation Strategies

After a careful review of MARTA’s vulnerabilities to the climate stressors expected to affect the agency’s service area, the study proposed adaptation strategies that could be implemented to address those vulnerabilities. Each strategy was categorized by the department responsible for its implementation, the climate stressor it addressed, and whether it could be implemented in the short-term or the long-term. Most short-term strategies involved either establishing thresholds for performing certain actions (e.g.

increased inspections of HVAC systems) or identifying assets, operations, materials, and locations vulnerable to different climate stressors beyond the more global vulnerability assessment conducted as part of this study. Most long-term strategies involved either updating design standards for new asset procurements or physically increasing the resiliency of the agency's assets (e.g. harden maintenance facilities against threat of flooding).

9.3 A Framework for MARTA and Other Agencies

Because the primary purpose of a transit asset management system is to prioritize the maintenance, rehabilitation, and replacement of an agency's assets within the context of its mission, goals, and funding constraints and because an agency's assets (and the activities related to them) are most likely to be affected by changes in the environment, this system provides a foundation through which climate adaptation can be addressed. The study discussed the history and current structure of MARTA's asset management program. In addition, the study used the FTA's forthcoming Asset Management Guide to analyze the maturity of the program. From this analysis, the study proposed a framework for how MARTA could address climate adaptation through its asset management program. This decision framework (also referred to as a "benefit-risk" framework) would incorporate climate hazards into the agency's capital improvement program, but prioritize their consideration into project decisions based on several factors, such as the impact of the hazard on the agency's ability to achieve its objectives (i.e. safe, reliable, cost-effective transit).

In addition to developing a framework for MARTA's transit asset management program, the study also proposed a general framework that other transit agencies could use to address climate adaptation through their asset management programs. This first included a discussion about the importance and basic components of a transit asset management system as well as how the FTA's forthcoming Asset Management Guide

would be a valuable resource for agencies seeking to establish their own asset management program or improve the capabilities of an existing program. Once a basic transit asset management program was established, the remaining steps of the general framework included establishing an agency-wide policy on climate change, conducting a climate change vulnerability assessment, identifying potential adaptation strategies, developing and implementing a climate adaptation plan, and monitoring and updating the framework as necessary.

9.4 Limitations and Further Research Needs

There are several limitations to this study and its conclusions that result in several areas for further research.

The first limitation of this study lies within the uncertainty in climate modeling. While a considerable amount of effort has been devoted to improving the ability of global-scale climate models to project future climate scenarios, the downscaling of the data used by these models to conduct climate projections on a more local level has much more uncertainty. As a result, only general conclusions can be made from these projections, which, while beneficial for beginning to address climate adaptation, still leave much to be desired. Therefore, further research should be conducted to improve climate-modeling projection methods for smaller geographic areas (such as regions and metropolitan areas). In addition, because many transit agencies do not have knowledge in climate science or experience in climate modeling, a simplified modeling process or tool should be developed to help agencies understand the potential climate hazards they may face in the future.

Another limitation of this study was with the climate vulnerability assessment that was conducted. This assessment only identified vulnerabilities based on a small sample of current staff knowledge. While the information collected through the interview process was very valuable, a more comprehensive climate vulnerability assessment should seek to

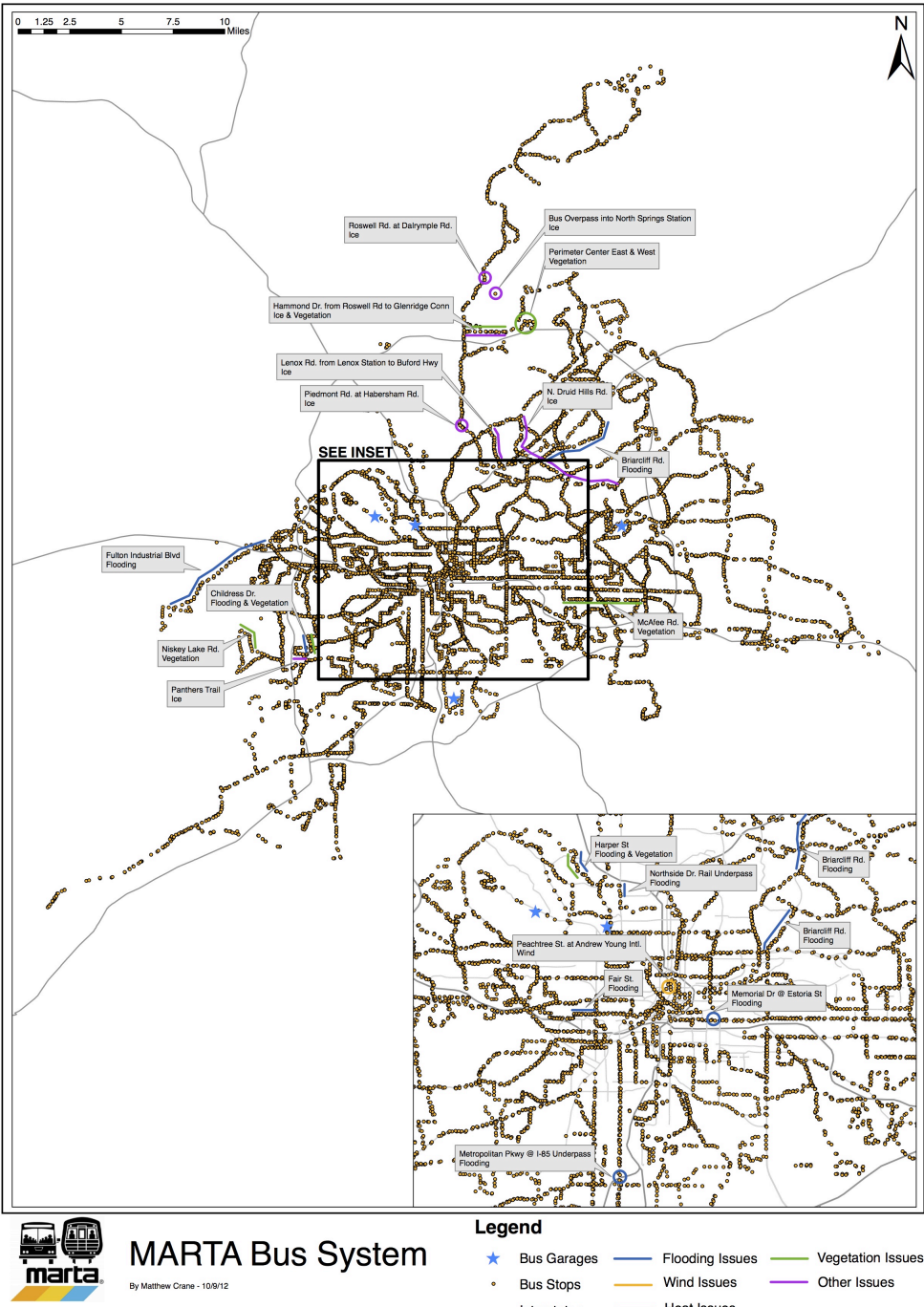
supplement the knowledge and experiences of its staff with an objective assessment of its asset inventory. Therefore, another area for further research would be the development of a standard climate assessment process for assessing the vulnerability (and/or resiliency) of different types of transit assets to various climate stressors.

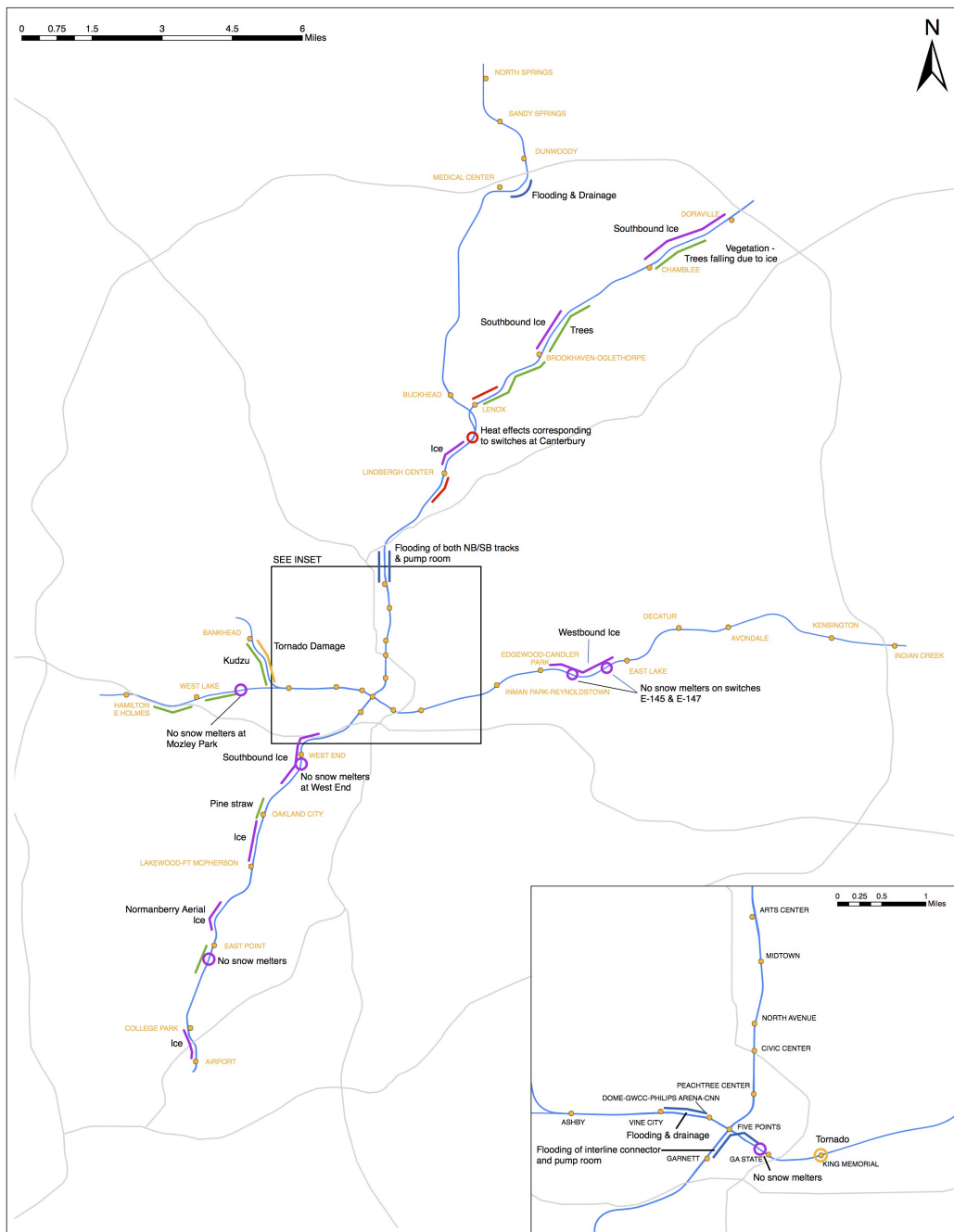
A third limitation of this study is the caution that should be taken in directly applying the lessons learned from the MARTA case study to other transit agencies (with the exception of the general framework proposed in the previous chapter). This is primarily because of characteristics that are unique to the MARTA system, such as its location, size, and the relatively high maturity of its asset management program. Therefore, lessons from this case study that can be applied to another agency should be applied in the context of the specific characteristics of the agency and – even more importantly – the environment in which it operates.

APPENDIX A

MAPS OF CLIMATE-VULNERABLE LOCATIONS IN MARTA'S

BUS AND RAIL NETWORKS





MARTA Rail System Legend

By Matthew Crane - 10/1/12

- MARTA Rail
- MARTA Stations
- Interstates
- Flooding Issues
- Wind Issues
- Heat Issues
- Vegetation Issues
- Other Issues

APPENDIX B

SUMMARY MATRIX OF MARTA INTERVIEWS

Climate Stressors	Heat waves (Higher extreme temps (>95F) for longer periods of time	Wider variation in temps	Higher-intensity precipitation in storm events (Possibility of increased flooding)	Increase in high-wind events (strong storms or tornadoes)	Droughts	Miscellaneous
Bus Maintenance	<ul style="list-style-type: none"> • CNG bus components can overheat due to their already-high operating temperature • HVAC systems are monitored more closely in the summer • Installed electric cooling system on buses (replaced hydraulic fans; one of the first transit agencies to do so) • New buses will have an 	<ul style="list-style-type: none"> • Transit buses in North American are designed to operate in a very wide range of environmental conditions, and so in general are very resilient 	<ul style="list-style-type: none"> • Not a serious concern since most bus routes do not pass through areas prone to flash flooding 	<ul style="list-style-type: none"> • Not of immediate concern; there have been no tornadoes in MARTA's service area for two years 	<ul style="list-style-type: none"> • Bus washing had to be reduced in the past, but MARTA is/has installed new wash racks that reduce water use by 90% through reclamation 	<ul style="list-style-type: none"> • Ice storms have the greatest impact to bus service, but are infrequent • Local power outages shut down maintenance facilities because the generators in place are not powerful enough to run the entire facility and its equipment

	electrically operated HVAC system					
Track & Structures	<ul style="list-style-type: none"> • While there were no major issues during this past summer's heat waves, heat is the most persistent problem for rail • If heat persists for long periods of time, the rail may need to be cut or the track might buckle • MARTA has very stringent standards for maintaining and replacing rail 	<ul style="list-style-type: none"> • Usually not stressful if it's a one day event, but consistent days can cause issues • 2-3 years ago, a cold snap in November resulted in rails breaking near the Five Points station 	<ul style="list-style-type: none"> • Sump pumps in several stations constantly remove groundwater to prevent flooding • GSU/Garnett interline connector is most vulnerable to flooding due to heavy precipitation events • Several steep slope areas along the ROW, but no significant issues with landslides due to intense rain 	<ul style="list-style-type: none"> • Not a critical issue for most infrastructure with the exception of the King Memorial station, which is the highest elevated station on the network and is surrounded by mostly flat, uncovered ground 	<ul style="list-style-type: none"> • Vegetation near the ROW can become a fire hazard during especially dry conditions 	<ul style="list-style-type: none"> • FRA regulations require all track to be inspected twice per week • Vegetation near the ROW can fall over from intense storms, wind, or ice events • Ice storms have the greatest impact to MARTA service because of potential freezing of the third rail

<p>Civil Engineering (Design)</p>	<ul style="list-style-type: none"> • A critical concern, but seems to be manageable for the near future 	<ul style="list-style-type: none"> • Not an immediate concern 	<ul style="list-style-type: none"> • A critical concern, but seems to be manageable for the near future • Runoff intensities from future developments could tax existing system • If maintenance is not performed properly and regularly, drains/pipes will clog 	<ul style="list-style-type: none"> • Not an immediate concern 	<ul style="list-style-type: none"> • Not an immediate concern 	<ul style="list-style-type: none"> • MARTA is currently going through the process of updating its design manual, which involves updating codes and standards and making the entire document available online
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Architecture	<ul style="list-style-type: none"> • Heat compounds issues with already-aged assets 	<ul style="list-style-type: none"> • Freeze-thaw cycles several years ago resulted in greatly deteriorated pavement 	<ul style="list-style-type: none"> • Many older roofs have almost no pitch, which causes water to pool on the roof during precipitation events 	<ul style="list-style-type: none"> • Not a concern 	<ul style="list-style-type: none"> • MARTA has made an effort to install hardier, local, drought-resistant plants in station areas, but even local vegetation has struggled during extreme conditions 	<ul style="list-style-type: none"> • Issues with assets (landscaping, platforms, roofs) are mainly a result of the general aging of the system, though factors such as weather and rider abuse also could have had an effect • MARTA primarily uses metal for new roofs since it is better able to withstand weather events and requires almost no maintenance after installation
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<p>Rail Vehicle Maintenance</p>	<ul style="list-style-type: none"> • Heat waves this summer were particularly intense and caused more issues than in previous years • Longer operating times than normal for HVAC systems resulted in an increase in failures • MARTA is developing a series of cost-effective solutions to address the cooling issues, starting with minor, everyday maintenance tasks and building up to new future specifications for replacement equipment 	<ul style="list-style-type: none"> • Does not have much impact on assets, but does on customer comfort 	<ul style="list-style-type: none"> • Flooding has not been an issue for rail vehicles, but the maintenance facilities (particularly Armour Yard) must be shut down if they are flooded because of the risk for electrocution from the high-voltage equipment located in the facilities • During intense precipitation, train operators may operate train in emergency braking mode if they feel the train is not stopping 	<ul style="list-style-type: none"> • Tornadoes and high wind events can cause rail vehicles to be damaged by flying debris • MARTA communication antennas installed on skyscrapers downtown and on Stone Mountain could also be damaged and disrupt MARTA communications 	<ul style="list-style-type: none"> • Vehicle washing has been impacted during droughts, but it is not an immediate concern 	<ul style="list-style-type: none"> • While cold temperatures do not have much of an impact, ice and ice storms can have a significant impact to MARTA's service • Before potential ice storms/icy conditions, MARTA has modified rail vehicles that can spray deicer on rails (both running and third) and have ice-scraping collector shoes that can remove ice buildup • MARTA has standard operating
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	<ul style="list-style-type: none"> Heat can be an issue for staff in maintenance facilities, but procedures are in place to prevent heat exhaustion 		properly, which causes damage to the wheels			<p>procedures in place to handle different weather conditions</p> <ul style="list-style-type: none"> Vegetation near the ROW has been an issue because it can obscure the vision of operators as the vehicle travels along the rail and falling limbs (or entire trees) can damage vehicles
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Capital Facilities	<ul style="list-style-type: none"> • One of the most critical concerns for MARTA 	<ul style="list-style-type: none"> • Not an immediate concern 	<ul style="list-style-type: none"> • Heavy precipitation events can overwhelm drains and pipes, causing flooding in tunnels and substations • A steep slope near the track ROW by the Medical Center station can cause mud and water to pool on the track during particularly heavy rain events or flooding 	<ul style="list-style-type: none"> • High winds (and freezing conditions) can cause vegetation to fall and block the track and/or damage assets (vehicles, rail, and ROW equipment) 	<ul style="list-style-type: none"> • Droughts have affected the washing of vehicles, but new water reclamation systems have reduced water use significantly • Armour Yard may use rainwater collection to provide water for vehicle washing 	<ul style="list-style-type: none"> • MARTA's feeder system design (buses feed into train network) can present challenges in severe weather conditions because of the reliance of the two systems on each other and their differing vulnerabilities to weather events • MARTA should also consider the cost of lost revenue when the loss of an asset affects service
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<p>Transit Asset Management/ State of Good Repair Program</p>	<ul style="list-style-type: none"> • First condition assessment conducted in the year 2000 collected condition data on a sample of 18,000 assets, which did not include vehicles • Second condition assessment (July 2011-October 2012) looked at all of MARTA's asset groups (approximately 55-60k total assets) and conducted its assessments on a statistically significant sample size of assets for each asset group • MARTA is currently working with Asset Works to develop and install a Capital Planning Module for the EAM system to automatically generate candidate CIP projects based on any information stored in the system. In addition, the new module will be able to look across different asset groups when prioritizing projects • The Expert Choice decision making tool is also being developed to assist the CIP committee in making decisions on which projects to include in the CIP utilizing a set of agency objectives that can be given different weights based on the agency's priorities • The EAM system currently has the ability to identify particular asset groups or specific types of assets as being vulnerable to climate change effects
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APPENDIX C

SUMMARY MATRIX OF CLIMATE ADAPTATION STRATEGIES

Climate Stressor		Heat waves	More intense precipitation during storms ¹	Droughts	Wider temperature variations	More frequent high-wind events ²
Department						
Bus Maintenance & Operations	Short-Term	<ul style="list-style-type: none"> -Establish explicit policies for conducting more frequent inspections of air conditioning systems and CNG buses during summer months and establishing temperature thresholds for increased inspections during other months -Evaluate existing policies on worker safety during hot days and update/clarify as necessary (thresholds) -Educate customers on ways to stay cool when waiting at a bus stop 	<ul style="list-style-type: none"> -Identify all flood prone areas on all bus routes -Ensure all bus storage facilities are above existing floodplains and not in flash-flood prone areas. If not, identify temporary storage locations if flood conditions are expected -Establish a bus-rerouting procedure for flood prone areas and a communication plan for affected customers -Establish a combined emergency shut down and facility restart plan for any bus 	<ul style="list-style-type: none"> -Establish modified bus washing plans for varying degrees of drought 	<ul style="list-style-type: none"> -Establish thresholds for increased inspection of bus cooling systems for both extreme hot and cold days -Examine potential impacts of wider temperature ranges on bus tire pressures 	<ul style="list-style-type: none"> -Establish thresholds for alternate routing or suspended service in areas vulnerable to high winds

			maintenance facility in a flood prone area and practice the plan with facility employees			
	Long-Term	<ul style="list-style-type: none"> -Update design standard for new buses to have heat-resistant materials where feasible, more efficient and durable engine cooling systems (especially for CNG buses), and more durable air conditioning systems -Install air conditioning systems in maintenance facility areas where feasible -Retrofit or redesign maintenance facilities to utilize natural air flow to cool facilities during summer months where air conditioning is unfeasible 	<ul style="list-style-type: none"> -Develop an alternative route schedule/plan for all flood-prone areas and communicate plan to customers -Incorporate more redundant routing into future bus plans -Relocate or harden maintenance facilities against flooding 	<ul style="list-style-type: none"> -Replace all bus washing equipment with more efficient systems (low-flow heads and water reclamation) -If efficient wash systems are already in place, utilize non-potable sources for wash water (rain barrels, groundwater, etc) -Investigate new paints or coverings that could be applied to reduce the frequency of washing 	<ul style="list-style-type: none"> -Incorporate materials that better withstand greater temperature ranges 	<ul style="list-style-type: none"> -Harden areas vulnerable to high winds -Harden bus storage facilities against damage from falling vegetation
Rail Vehicle Maintenance & Operations	Short-Term	<ul style="list-style-type: none"> -Conduct more frequent inspections of air conditioning and electrical systems during summer months 	<ul style="list-style-type: none"> -Establish a combined emergency shut down and facility restart plan for any rail maintenance facility in 	<ul style="list-style-type: none"> -Establish modified railcar washing plans for varying degrees of drought 	<ul style="list-style-type: none"> -Identify materials and components that are most impacted by 	<ul style="list-style-type: none"> -Establish thresholds for slow orders or suspended service on elevated track

		and establish thresholds for increased inspections during other months -Evaluate existing policies on worker safety during hot days and update/clarify as necessary (thresholds)	a flood prone area and practice the plan with facility employees -Develop alternative techniques that train operators can employ to stop trains properly without enabling emergency braking mode		wider temperature ranges	structures and stations
	Long-Term	-Update design standard for new railcars to have heat-resistant materials where feasible, increased ventilation for electrical components, and more durable air conditioning systems -Upgrade air conditioning on existing railcars with systems that are designed for longer operating cycles	-Relocate or harden maintenance facilities against flooding	-Replace all railcar washing equipment with more efficient systems (low-flow heads and water reclamation) -If efficient wash systems are already in place, utilize non-potable sources for wash water (rain barrels, groundwater, etc) -Investigate new paints or coverings that could be applied to reduce the frequency of washing	-Incorporate materials that better withstand greater temperature ranges	-Institutionalize modified operating procedures for high wind conditions
Track &	Short-	-Develop an explicit	-Conduct more	-Identify and	-Identify track	-Identify and

Structures	Term	<p>policy that establishes thresholds for conducting more frequent inspections during hot days or heat waves</p> <p>-Unify and re-evaluate policies regarding inspecting, maintaining, and replacing rail and track elements during extreme weather conditions</p>	<p>frequent inspection of drains and pipes located near tunnel entrances and on aerial structures to check for clogging</p>	<p>remove vegetation that may pose a fire hazard during drought conditions in MARTA's ROW</p> <p>-Develop a plan with stakeholders located next to ROW for identifying and removing hazardous vegetation during drought conditions</p>	<p>areas that are vulnerable to large temperature ranges and fluctuations</p>	<p>remove vegetation within MARTA's ROW that may pose a falling or debris hazard</p> <p>-Develop a plan with stakeholders located next to ROW for identifying and removing hazardous vegetation</p> <p>-Establish wind speed thresholds for suspending service to King Memorial Station</p>
	Long-Term	<p>-Replace track elements and rail with more heat-resistant materials and expansion joints</p>	<p>-Increase drainage capacity near tunnel entrances and on aerial structures</p>	<p>-Establish a process for regularly identifying and removing hazardous vegetation within and near the ROW</p>	<p>-Install systems (e.g. expansion joints) that allow rail to expand and contract without compromising system speed or rail integrity</p>	<p>-Establish a process for regularly identifying and removing hazardous vegetation within and near the ROW</p> <p>-Retrofit King Memorial station to withstand higher wind speeds</p>

Civil Engineering/Design	Short-Term	-Continue to monitor how extreme heat and heat waves affect facilities, materials, and assets	-Coordinate with future developers to reduce water runoff into MARTA's ROW -Establish policies and procedures for regularly inspecting and clearing clogged drains and pipes -Be aware of pending updates to FEMA floodplain maps		-Identify and monitor structures and materials vulnerable to large temperature fluctuations	-Identify areas where further protection from strong winds is required
	Long-Term	-Update design standards as necessary to incorporate heat-resistant materials where possible and feasible	-Incorporate higher flood design standards for facilities, pipes, and drains -Incorporate low-impact developments (rain gardens, bioswales, etc) into the design of new facilities to reduce runoff	-Incorporate water-saving mechanisms (e.g. low-flow toilets) and grey water usage into design standards	-Incorporate materials that can withstand a wider range of temperatures in design standards	-Modify design standards to account for greater wind velocities
Capital Facilities	Short-Term	-Coordinate all heat-related adaptation efforts from other departments -Conduct detailed analysis of the effect of heat waves on major capital assets	-Identify areas along MARTA's ROW with steep slopes and strategies for preventing mudslides during heavy precipitation events -Harden most vulnerable capital	-In relevant areas (e.g. bathrooms), post information on how to conserve water	-Identify energy and water use metrics -Measure energy consumption and water usage	-Prepare an alternative communication plan and distribute back-up communication equipment to most critical staff and operators

			facilities against flooding			
	Long-Term	-Replace major capital facilities with new designs that incorporate heat-resistant materials	<ul style="list-style-type: none"> -Increasing pumping capacity at underground rail stations -Implement strategies for preventing mudslides on steep slopes -Abandon most-vulnerable major capital facilities and/or replace existing facilities with new facilities that incorporate more stringent flood design standards -Incorporate future floodplains when siting new major capital facilities -Evaluate feasibility of providing shelters at bus stops with no shelter 	<ul style="list-style-type: none"> -Mandate water saving/reduction plans for new/rehabilitated facilities -Install water-efficient faucets, water fountains, and cleaning apparatuses 	-Retrofit existing buildings to meeting “green” building design standards; seek to certify new buildings to LEED or similar standards	-Install back-up communications systems that can be activated if primary systems fail
Architecture	Short-Term	-Conduct an assessment of available shade near all bus stops and develop a plan for	-Develop and implement a coordination effort with local communities and	-Try to better protect newly-installed vegetation from	-Develop a station floor replacement prioritization	-Identify potential landscape designs (natural or manmade) that can

		improving shade conditions near most vulnerable stops first -Similar shade assessment for rail stations -Evaluate methods for improving natural cooling in rail stations during hot days	governments to reduce runoff from existing and planned future developments -Develop a roof replacement prioritization plan for all rail station roofs that have no pitch and/or have exceeded their expected useful life	customer abuse	plan -Identify new materials and installation techniques that are more resistant to freeze-thaw cycles	reduce or better withstand greater wind velocities
	Long-Term	-Increase shaded areas leading up to and around all bus stops, especially those without shelters (and rail stations) -Employ methods for improving natural cooling in stations -If natural cooling methods are not feasible or possible, enclose rail stations and install air conditioning	-Incorporate low-impact developments (rain gardens, bioswales, etc) into station design and areas leading up to bus stops -Replace original roofs with more durable, weather-resistant materials and a pitch to allow water to drain properly -Roof replacements should include installation of low-impact developments to capture and filter rainwater runoff	-Utilize rainwater captured from new roofs to water vegetation near stations	-Replace most exposed station platforms with more durable, weather-resistant materials	-Incorporate aesthetic elements that also block or reduce wind velocities
General/Misc	<ul style="list-style-type: none"> • Adopt an agency-wide policy on climate change and climate adaptation and mitigation • Conduct climate vulnerability and risk assessment for assets and operations 					

	<ul style="list-style-type: none"> • Develop and implement a climate change adaptation and mitigation plan • Utilize existing agency processes and standard operating procedures to implement adaptation/mitigation strategies • Install sufficient generator capacity to entirely power bus maintenance facilities and their equipment during power outages • Review and update standard operating procedures for extreme weather conditions to incorporate emergency evacuation and restart plans for maintenance facilities and alternative communication plan • Develop a system accessibility plan which should establish what level of service will be provided during or after extreme weather events (ice storm, floods, etc) as well as how access to that service will be maintained (e.g. snow/ice removal) • Coordinate with local weather services to identify extreme weather events within the service area in real time <p>Allow system users (passengers) to crowd source updates via social media (like Twitter) (e.g. flooded routes, broken A/C in train cars and buses) to key agency personnel</p>
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